# *Journal*

*of*

# THE ROYAL AERONAUTICAL SOCIETY

FEBRUARY 1957

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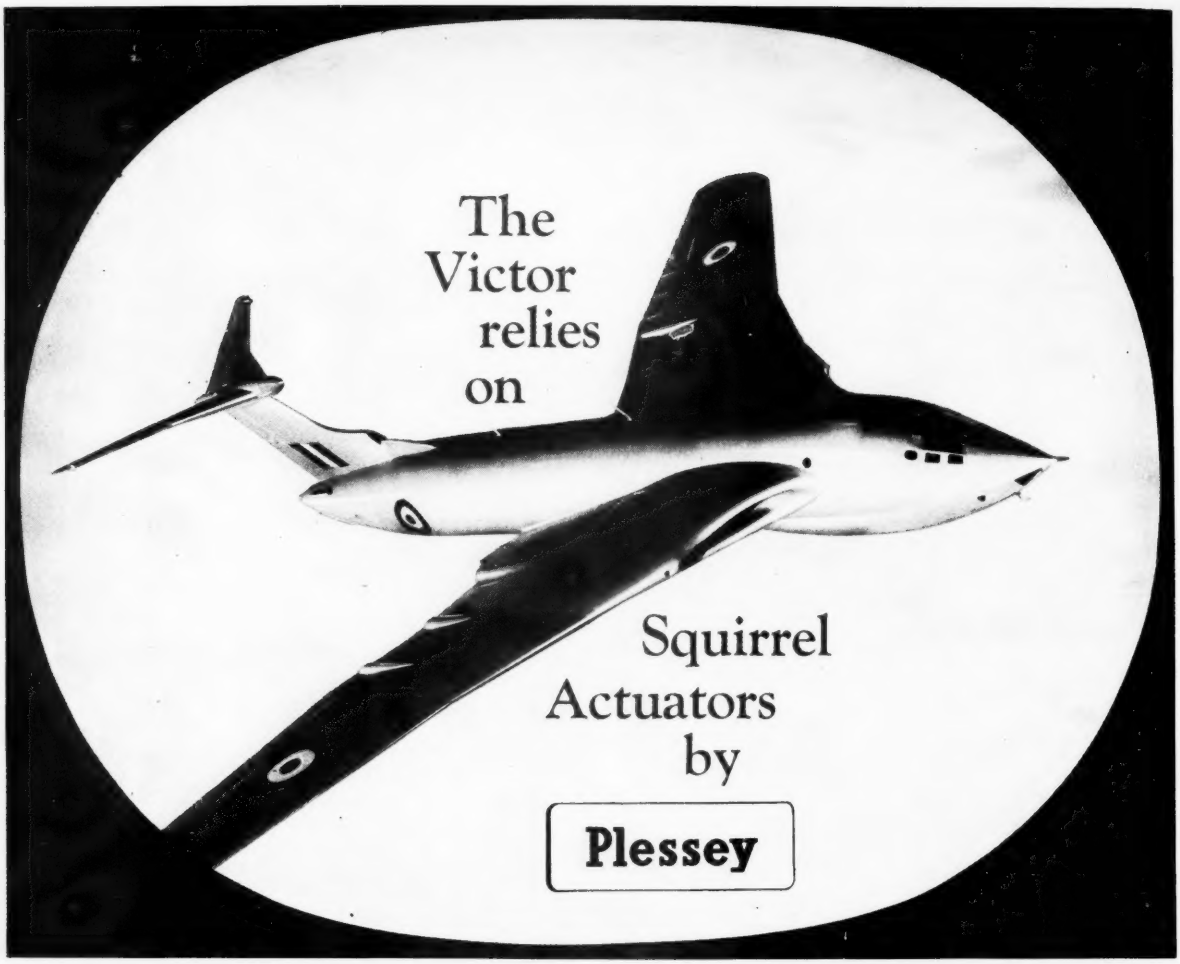


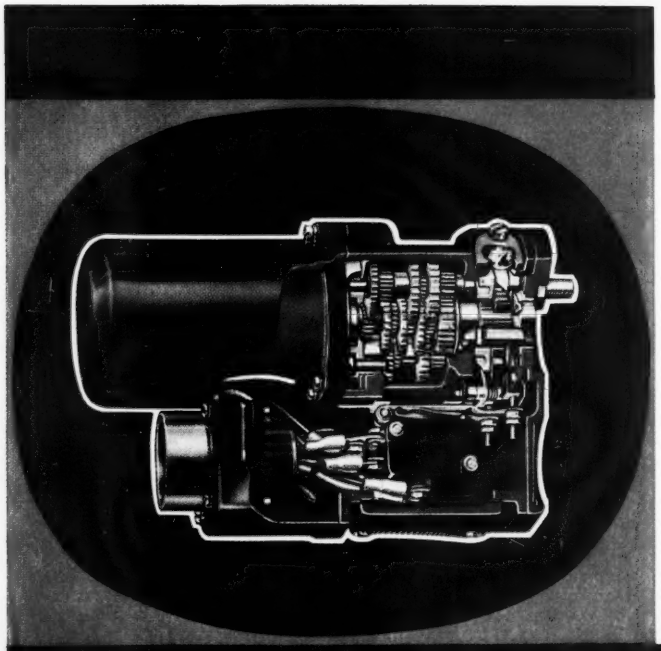

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*All communications for publication in, and advertisements for, the* JOURNAL *should be addressed to the Editor,* JOAN BRADBROOKE, *A.R.Ae.S.; all communications on general matters affecting the Society should be addressed to the Secretary,* A. M. BALLANTYNE, *T.D., B.Sc., Ph.D., Hon.F.C.A.I., A.F.I.A.S., F.R.Ae.S.*

*None of the papers or paragraphs must be taken as expressing the opinion of the Council of the Royal Aeronautical Society unless otherwise stated.*


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# NOTICES

*An annual sum of £250 is available for premium awards for papers, including Technical Notes, published in the Journal. Members and non-members of the Society are invited to submit papers on any aspect of aeronautics*

### Nomination of Candidates for Council

The following is an extract from the By-Laws:—

"The Twenty-one ordinary members (of the Council) shall be nominated and elected from among the members of the Society. At the date of their election at least ten shall be Fellows, and one at least shall be in each of the following classes: Associate Fellow, Associate and Graduate.

"Of the ordinary members of the Council, that number necessary to create seven vacancies shall retire annually. The retiring members shall be those with the longest service since their last election but they shall be eligible for re-election.

"Nominations of candidates for election to the Council must be received by the Secretary not later than 10th April in each year and shall include statements in writing by the candidates that they are willing to serve. The nomination forms shall be signed by one proposer and two seconders, all of whom shall be Voters."

Nomination forms may be obtained on application to the Secretary.

### Main Lecture at Halton Branch—Change of Venue

Attention is drawn to the fact that the Main Lecture "Synthetic Aids to Flying Training" by W. Makinson and G. M. Hellings which is to be given at the Halton Branch on Thursday 7th February will be held at the *Station Concert Hall, R.A.F., Halton*, at 6.30 p.m. and not at the Canteen, Air Trainers Ltd., Aylesbury. It is regretted that the latter address was given in error.

### Acknowledgment

The Council acknowledges with grateful thanks back numbers of the Journal from Commander F. W. N. Bassett, *Associate Fellow*.

### Lost Property

The Society has two pairs of spectacles which have been left in the building. One pair, found in the Council room after a meeting early in December, is in a blue case with inside the lid the name "A. E. Farmer, Consulting Optician, Cheam." The second pair has no case and was found in the entrance hall after the Graduates' and Students' Dance at the end of November.

A pipe with a round bowl and four-sided black stem with the trade name "Captain Black" and number B594T is also waiting to be claimed.

### The Physical Society's Forty-first Exhibition of Scientific Instruments and Apparatus

The Forty-first Exhibition of Scientific Instruments and Apparatus will be held by the Physical Society from 25th to 28th March 1957 at the Royal Horticultural Halls, Westminster, S.W.1, from 10.30 a.m. to 7 p.m. (On 25th March the exhibition will be open until 2 p.m. and on 28th March until 4.30 p.m., only.) A limited number of tickets for members of the Royal Aeronautical Society have been made available and application for tickets, stating the choice of day, should be made to the Secretary at 4 Hamilton Place, London, W.1.

### New Year's Honours List

| | |
|---|---|
| Knight Batchelor | G. R. Edwards (*Fellow*) (President-Elect) |
| C.B.E. | James Martin (*Fellow*)<br>Air Cdre. M. E. M. Perkins (*Associate Fellow*)<br>Group Capt. F. F. Wicks (*Associate Fellow*) |
| O.B.E. | Group Capt. J. H. Hunter-Tod (*Associate Fellow*)<br>Group Capt. A. J. Mott (*Associate Fellow*)<br>R. D. Peggs (*Fellow*)<br>A. J. Penn (*Fellow*)<br>Wing Cdr. R. C. Preston (*Associate Fellow*) |

### American Honours Awarded to Members

The National Aeronautic Association's Elder Statesmen of Aviation Award Committee have presented awards to the following members of the Society:

Igor I. Sikorsky (*Honorary Fellow*)
Grover Loening (*Fellow*)

The Institute of the Aeronautical Sciences have included the following members in their awards list:

*Honorary Fellowship* to Air Cdre. F. R. Banks (*Fellow*) This is the highest honour the Institute can bestow.

*Fellowship* to Professor A. R. Collar (*Fellow*) and to Stewart Scott Hall (*Fellow*).

Edwin E. Aldrin (*Associate Fellow*) and Earl D. Osborn (*Associate Fellow*) have been elected Vice-Presidents of the Institute of the Aeronautical Sciences.

### The Tenth Louis Bleriot Lecture

The Tenth Louis Bleriot Lecture will be delivered in London on Thursday 7th March 1957 at the Institution of Mechanical Engineers, Birdcage Walk, S.W.1, at 6 p.m. (Tea at 5.30 p.m.) The Lecture entitled "New Methods of Aircraft Production" will be given by Monsieur Paul Badre, Director of Production at Ouest Aviation (Société Nationale de Constructions Aéronautiques) formerly known as Société Nationale de Constructions Aéronautiques du Sud-Ouest.

### Associate Fellowship Examinations, June 1957

Entries for the next Associate Fellowship Examination should be received from Candidates in the British Isles by 28th February 1957. The closing date for entries outside the United Kingdom was 31st December 1956.

### Institute of Navigation

A lecture will be given before the Institute of Navigation on 15th February at 5.15 p.m. by D. O. Fraser entitled "Navigation and Traffic Control over the North Atlantic." It is an examination of the relationship between traffic control and navigation in North Atlantic air operations. The lecture is at the Royal Geographical Society, 1 Kensington Gore, London, S.W.7.

# DIARY

## LONDON

**7th February**

MAIN LECTURE AT HALTON BRANCH.—Synthetic Aids to Flying Training. W. Makinson and G. M. Hellings. Station Concert Hall, R.A.F., Halton. 6.30 p.m. *Note change of venue.*

12th February

JOINT LECTURE WITH THE HELICOPTER ASSOCIATION OF GREAT BRITAIN.—Vibration Problems Associated with the Helicopter. O. L. L. Fitzwilliams. Library, 4 Hamilton Place, London, W.1. 7 p.m.

14th February

MAIN LECTURE.—The Fairey Delta. R. L. Lickley and L. P. Twiss. Institution of Mechanical Engineers, Birdcage Walk, London, S.W.1. 6 p.m. (Tea 5.30 p.m.)

26th February

SECTION LECTURE.—Recent Advances in the Design of Aircraft Tyres and Brakes. H. W. Trevaskis. Library, 4 Hamilton Place, London, W.1. 7 p.m.

**7th March**

TENTH LOUIS BLERIOT LECTURE.—New Methods in Aircraft Production. P. Badré. Institution of Mechanical Engineers, Birdcage Walk, London, S.W.1. 6 p.m. (Tea 5.30 p.m.)

12th March

SECTION LECTURE.—High Temperature Materials for Engines. E. R. Gadd. Library, 4 Hamilton Place, London, W.1. 7 p.m.

21st March (transferred from 26th March)

SECTION LECTURE.—The Application of Automatic Digital Computers to Aeronautical Problems. Dr. S. H. Hollingdale. Library, 4 Hamilton Place, London, W.1. 7 p.m.

26th March (transferred from 17th December, 1956)

MAIN LECTURE AT READING BRANCH.—Present and Future Developments in Civil Aviation. P. G. Masefield, Great Western Hotel, Reading. 6.30 p.m.

**4th April**

MAIN LECTURE.—Engine-Airframe Integration. L. F. Nicholson. Institution of Mechanical Engineers, Birdcage Walk, S.W.1. 6 p.m. (Tea 5.30 p.m.)

## GRADUATES' AND STUDENTS' SECTION

**13th February**

THE AREA RULE.—W. T. Lord. Library, 4 Hamilton Place, London, W.1. 7.30 p.m.

16th February

VISIT TO THE SOUTHERN AIR TRAFFIC CONTROL CENTRE, M.T.C.A., Bath Road, Harmondsworth, Middlesex. 10.30 a.m.

**5th March**

ANNUAL GENERAL MEETING AND FILM SHOW. Library, 4 Hamilton Place, London, W.1. 7.30 p.m.

19th March

GAS TURBINES FOR HELICOPTERS.—A. W. Morley. Library, 4 Hamilton Place, London, W.1. 7.30 p.m.

## BRANCHES

**7th February**

**Cheltenham.**—Problems of Progressive Failure. Sir Alfred Pugsley, O.B.E. St. Mary's College, Cheltenham. 7.30 p.m.
**Halton.**—MAIN LECTURE.—Synthetic Aids to Flying Training. W. Mckinson and G. M. Hellings. Station Concert Hall, R.A.F., Halton. 6.30 p.m.

13th February

**Leicester.**—Flight Development of Modern Prototype Aircraft. C. F. Bethwaite. Lecture Theatre, Loughborough College, Leicester. 6.30 p.m.

15th February

**Birmingham.**—President's Night. DC-7 Film. High-Speed Flying. E. Gunn. Birmingham Engineering Centre, Stephenson Place, Birmingham. 7.15 p.m.
**Brough.**—Annual Dinner and Dance. Jackson's Ballroom, Hull.

18th February

**Henlow.**—New Methods of Approach to Airworthiness. W. Tye, O.B.E. Building No. 62, R.A.F. Technical College, Henlow. 7.30 p.m.

19th February

**Belfast.**—Lecture on Welding. K. A. Peel. Kensington Hotel, Belfast. 7 p.m.

20th February

**Bristol.**—Viscount. B. E. Stephenson. Conference Room, Filton House, Bristol Aeroplane Co. Ltd. 6 p.m.
**Brough.**—Prospects and Problems in the Use of Nuclear Energy. Prof. G. F. J. Garlick. Lecture Hall, Yorkshire Electricity Board, Ferensway, Hull. 7.30 p.m.
**London Airport.**—Independents VS, State Airlines. Mr. Curtis. Fairey's Lecture Hall. 6 p.m.
**Manchester.**—Flying Experiences. Capt. O. P. Jones, C.V.O., O.B.E. Reynolds Hall, College of Technology, Manchester. 7.30 p.m.
**Southampton.**—Branch Prize Papers. Lecture Theatre, Institute of Education, University of Southampton. 7 p.m.
**Weybridge.**—The Investigation of Aircraft Accidents. E. L. Ripley, O.B.E. Apprentice Training School, Vickers-Armstrongs (Aircraft) Ltd. 6 p.m.

21st February

**Isle of Wight.**—The Training of Aeronautical Engineers. Prof. A. R. Collar. Clubhouse, Saunders-Roe Sports and Social Club, Church Path, E. Cowes. 6.30 p.m.
**Merthyr Tydfil.**—Some Lubrication Problems. D. O. MacDougall, D.F.C., B.O.A.C., Treforest.
**Yeovil.**—Second Henson and Stringfellow Memorial Lecture. Replacement of Piston Engines by Gas Turbines in Airliners. H. Sammons, C.B.E. Park School, Park Road (off Princes Street), Yeovil. 7.30 p.m.

25th February

**Glasgow.**—Members' Night. Royal Technical College, Glasgow. 7.15 p.m.

27th February

**Christchurch.**—Lecture Competition. King's Arms Hotel, Christchurch. 7.30 p.m.
**Preston.**—The Investigation of Aircraft Accidents. E. L. Ripley, O.B.E., R.A.F. Association, Preston. 7.30 p.m.
**Reading.**—Boundary Layer Control and its Engineering Aspects. Dr. G. V. Lachmann and J. B. Edwards. Western Manufacturing (Reading) Ltd. Canteen. 6 p.m.

**4th March**

**Derby.**—Problems of Rocket Development and Supersonic Flight. A. V. Cleaver. Rolls-Royce Welfare Hall, Nightingale Road, Derby. 6.15 p.m.
**Henlow.**—Bird Flight. Dr. R. H. J. Brown. Building No. 62, R.A.F. Technical College, Henlow. 7.30 p.m.

5th March

**Boscombe Down** (provisional).—Film and/or Medal Lecture Evening. Lecture Hall, A. & A.E.E. Boscombe Down. 5.45 p.m.

6th March

**Chester.**—A Century of Aeronautical Research, 1804-1903. J. Laurence Pritchard. Grosvenor Hotel, Chester. 7.30 p.m.
**Gloucester.**—Flying Boats. H. Knowler. The Wheatstone Hall, Brunswick Road, Gloucester. 7.30 p.m.
**Luton.**—Advantages and Disadvantages of Swept Wings. D. Küchemann. Napier Senior Staff Canteen, Luton Airport. 6.15 p.m.

7th March

**Belfast.**—Viscount Operation. E. R. Major. Kensington Hotel, Belfast. 7 p.m.

**DIARY**—*continued*

13th March

**Bristol.**—Fourth Barnwell Memorial Lecture. The Economy of Structures. Sir Alfred Pugsley, O.B.E. Main Lecture Theatre, University Engineering Laboratories, University Walk, University of Bristol. 7 p.m.
**Manchester.**—Second Chadwick Memorial Lecture. The Influence on Aircraft of Aeronautical Research. M. B. Morgan. Reynolds Hall, College of Technology, Manchester. 7.30 p.m.
**Southampton.**—Production Development. L. G. Burnard. Lecture Theatre, Institute of Education, University of Southampton. 7 p.m.
**Weybridge.**—The Problems of Jet Transport Operation. J. T. Dyment. Apprentice Training School, Vickers-Armstrongs (Aircraft) Ltd. 6 p.m.

14th March

**Isle of Wight.**—Fleet Air Arm Tactics and Strategy. Capt. D. R. F. Cambell, D.S.C. Clubhouse, Saunders-Roe Sports and Social Club, Church Path, E. Cowes. 6.30 p.m.
**London Airport.**—Problems of Jet Transport Operation. J. Dyment. Viking Centre Cinema.

15th March

**Birmingham.**—Medical Aspects of High-Speed Flying. Gp. Capt. W. K. Stewart. Birmingham Engineering Centre, Stephenson Place, Birmingham. 7.15 p.m.

18th March

**Derby.**—Joint Lecture with Institution of Mechanical Engineers. Operational Problems of Jet Airliners. W. O. W. Challier. Rolls-Royce Welfare Hall, Nightingale Road, Derby. 6.15 p.m.
**Henlow.**—Films. Building No. 62, R.A.F. Technical College, Henlow. 7.30 p.m.

19th March

**Glasgow.**—Titanium. R. L. Preece. Royal Technical College, Glasgow. 7.15 p.m.

20th March

**Brough.**—High Speed Flight. Col. Charles Yeager, U.S.A.F. Lecture Hall, Yorkshire Electricity Board, Ferensway, Hull. 7.30 p.m.
**Christchurch.**—Aviation Journalism. C. Gardner. King's Arms Hotel, Christchurch. 7.30 p.m.
**Merthyr Tydfil.**—Talk by member of the Douglas Aircraft Co. Inc. B.O.A.C. Treforest.

21st March

**Yeovil.**—Fundamental Particles of Physics. C. C. Butler. Park School, Park Road (off Princes Street), Yeovil. 7.30 p.m.

26th March

**Reading.**—MAIN LECTURE.—Present and Future Developments in Civil Aviation. P. G. Masefield. Great Western Hotel, Reading. 6.30 p.m.

27th March

**Leicester.**—Helicopters. Raoul Hafner. Lecture Theatre, Loughborough College, Leicester. 6.30 p.m.
**Luton.**—Annual General Meeting followed by Presidential Address. Napier Senior Staff Canteen, Luton Airport. 6.15 p.m.
**Preston.**—Aerial Survey. B. J. Atwell. Queen's Hotel, Lytham. 7.30 p.m.

28th March

**Bristol.**—Annual General Meeting. Film Show. Conference Room, Filton House, Bristol Aircraft Ltd. 6 p.m.
**Isle of Wight.**—Rocket Motors. Sidney Allen. Clubhouse, Saunders-Roe Sports and Social Club, Church Path, E. Cowes. 6.30 p.m.

## NEWS OF MEMBERS

Dr. KENNETH G. BERGIN (*Fellow*) has been appointed Chief Medical Officer of B.O.A.C.

A. M. CREEDON (*Associate Fellow*) is now employed by Condesco Ltd. as Chief Stressman at their Palmers Green Office.

P. A. DRILLIEN (*Associate*) has relinquished his position as Propeller Engineer at D. Napier and Son Ltd. and is now a Deputy Project Engineer at de Havilland Propellers Ltd., Hatfield.

T. E. FORD (*Associate Fellow*) has left Bristol Aircraft Ltd. to take up a position as Stressman with the de Havilland Aircraft Co. Ltd.

R. P. HARRINGTON (*Associate Fellow*), formerly Professor and Head of the Department of Aeronautical Engineering at the Rensselaer Polytechnic Institute, is taking up a post as Director of the Training Centre for Experimental Aerodynamics in Belgium.

Wing Cdr. E. G. MONK (*Associate Fellow*) has relinquished his position as Sales Manager of the Aviation Division of Elliott Brothers (London) Ltd. and has joined the Bendix Aviation Corporation of the U.S.A. as Regional Manager, United Kingdom.

N. H. PAYNE (*Associate Fellow*) has been appointed a Director of Dowty Fuel Systems Ltd.

M. J. RANT (*Associate Fellow*), formerly with Smiths Aircraft Instruments Ltd. at Bishop's Cleeve, nr. Cheltenham, is now Senior Technical Representative for S. Smith and Sons (Canada) Ltd.

N. O. RAWLINSON (*Associate Fellow*), formerly Personal Assistant to the General Manager of Airwork Ltd., is now a technical sales representative with Esso Petroleum Co. Ltd.

S. G. ROBBINS (*Companion*) has now taken employment with the Boeing Airplane Co. as a tool engineer in the machine planning group of their Transport Division, U.S.A.

G. M. SHIPWAY (*Associate*), formerly of Aviation Division, Dunlop Rubber Co., has now joined the Export Sales Department of the Aero Engine Division, Rolls-Royce Ltd., Derby.

T. THORNTON (*Graduate*), formerly of Aviation and Engineering Projects Ltd., is now at the Stress Office of the Fairey Aviation Co. Ltd.

K. W. WATKINS (*Associate Fellow*) is now a Section Leader in the Design Department of Ferry Airports Ltd., Blackbushe Airport, Camberley.

D. G. YOUNG (*Graduate*), having been awarded the Diploma of the College of Aeronautics, is now employed as a Development Engineer in the Guided Weapons Division of Elliott Brothers (London) Ltd.

## ELECTIONS

The following is a list of new members and transfers of membership of the Society:—

*Associate Fellows*

Basil Henry Arkell (*from Associate*)
John Salvatore Attinello
Jack Bligh
William Gregory Felix Burns
Henry Joseph de Barro
Frank Dove
Reginald Thomas Elvish
Ivan Beresford Holmes (*from Associate*)
Maurice Louis Hurel
Francis Murphy (*from Associate*)
Tadeusz Papis
Owen Alfred Saunders
Max Wingfield Wholey

*Associates*

James Scriven Bartlett (*from Student*)
Harold Murdoch Cameron
Norman Davies
Stanley Andrew Edward Griffiths
Harry Hudson
Joseph Neil Kingsmill Moncrieff
Peter Preece
Edward Reader
Albert Leslie Stabb
William Craig Timoney
Edward Percy Tyler
John Colin Walker
James Henry Wilcockson

New Members and Transfers—*continued*

*Graduates*

John Frederick Coplin (*from Student*)
George Eric Deadman (*from Student*)
Michael Charles Frengley (*from Student*)
Francis Vincent Mitchell
Trevor John Padwick
Ronald Alfred Pickering
Harold Leslie Rose
Robin Herrington Ryder (*from Student*)
Michael Gerald Stevens
Dennis Charles Wakeman
Bryan Williams
Sidney James Young
Czeslaw Andrzej Zborowski (*from Student*)

*Students*

John Stanley Alker
Jeffery Bruce Allen
Barry William Barnes
Michael Barrie Christopher
Eric Oliver Cocksworth
Patricia Noeline Cowgill
Norman John Davis
George Howard Davison
John Warren Joseph Farrell
Sylvia Findley
Ian Archibald Fisher
John Foxon
Alan Christopher Goodliffe
Preti Mohan Goyal
Anthony Errol Harris
Geoffrey Armstrong Hingley
Godfrey Robert Carr Hughes
Hugh Rupert Hughes
David John Leeding
Brian Maskew
Frank Lewis Matthews
Michael Gerald Moorhouse
Robin Vesty Myers
George Pandelis Nicholaidis
Michael David Parry
Brian Thomas Phillips
Michael Walter Ratcliffe Seel
Bohdan Olgierd Szuprowicz
Philip George Thompson

*Companions*

John Charles Raettig
Mulakala Yoganandam

### Changes of Address or Appointment

To assist in keeping the records of members correct and up to date the Secretary will be glad if all members will notify him as soon as possible of changes of address. He would also like to know of any change of appointment.

When notifying changes please give the following particulars:—

Name (in block letters). Grade of Membership.
New address (in block letters). Old address.

New appointment.—Please give name and address of employer and position held.

Changes of address must be received *before the 15th of the month* in order to be effective for the JOURNAL for the following month.

### Annual Subscriptions

Members are reminded that their annual subscriptions became due on 1st January 1957. The rates are:—

| | Home £ s. d. | Abroad £ s. d. |
|---|---|---|
| Fellows | 5 5 0 | 4 4 0 |
| Associate Fellows | 4 4 0 | 3 3 0 |
| *Associates | 3 3 0 | 3 3 0 |
| Graduates (aged under 26) | 2 2 0 | 2 2 0 |
| Graduates (aged 26 and over) | 2 12 6 | 2 12 6 |
| Students (aged under 21) | 1 1 0 | 1 1 0 |
| Students (aged 21 and over) | 1 11 6 | 1 11 6 |
| Companions | 3 3 0 | 3 3 0 |
| Founder Members | 2 2 0 | 2 2 0 |

*Any Associate elected before 1st October 1947 may, if he wishes, elect not to receive the JOURNAL, and in this case his subscription will be reduced by £1 1s. 0d. to £2 2s. 0d.

It will avoid delay and confusion if members, when sending remittances for subscriptions, will state their names clearly and give their addresses and grades of membership. Remittances should be made payable to the Royal Aeronautical Society.

### New Prices for Journal Binding

We regret that because of increased costs in the printing and publishing trade during this past year, prices for the permanent binding of Journals have had to be increased for 1957. The new charges will be:—

*Permanent Binding*

1956 Volume (including packing and postage) £1 2s. 6d.
Previous Volumes (including packing and postage) £1 4s. 0d.

Journals, with a note of the name and address of the sender, should be sent direct to The Lewes Press, Friars Walk, Lewes, Sussex, and the remittance to the Secretary at the Offices of the Society.

Members are asked to be certain that the address to which they want their Journals sent is the same on their letters to the Lewes Press and to the Society.

*Self-Binder Cases*

Self-Binder cases of the "Easibind" type to hold 12 Journals (cost 11s. 6d. each) are available from the offices of the Society.

*The Journal of the Royal Aeronautical Society*

WITH WHICH IS INCORPORATED THE INSTITUTION OF AERONAUTICAL ENGINEERS

VOLUME 61 FEBRUARY 1957 NUMBER 554

*Twelfth British Commonwealth and Empire Lecture*

# Aeronautical Development in Australia and its Potential Contributions to the British Commonwealth

by

L. P. COOMBES, D.F.C., B.Sc., F.C.G.I., F.I.A.S., F.R.Ae.S.

*(Chief Superintendent, Aeronautical Research Laboratories, Melbourne and President, Australian Division of the Society)*

The Twelfth British Commonwealth and Empire Lecture "Aeronautical Development in Australia and its Potential Contributions to the British Commonwealth" was given by Mr. L. P. Coombes, D.F.C., B.Sc., F.C.G.I., F.I.A.S., F.R.Ae.S., Chief Superintendent, Aeronautical Research Laboratories, Melbourne, before the Society on 22nd November 1956 at the Institution of Mechanical Engineers. Mr. E. T. Jones, C.B., O.B.E., F.R.Ae.S., President of the Society, presided and introduced the Lecturer.

MR. E. T. JONES: The British Commonwealth and Empire Lecture was given annually and normally alternated yearly between a resident of the United Kingdom and a resident of a member country of the Commonwealth. This year the lecture was to be given by a resident of Australia and it was his great pleasure to introduce Mr. Coombes. Mr. Coombes had long been a friend and colleague of many of them but as they had a fair number of the younger generation present he would introduce Mr. Coombes properly.

Mr. Coombes had served the profession of aeronautics since 1917 when he started as a pilot in the First World War. For these services he was awarded the Distinguished Flying Cross. He was a Fellow of the Society and a Fellow of the Institute of the Aeronautical Sciences. He was also a Fellow of the City and Guilds Institute. Mr. Coombes was elected Chairman of the Melbourne Branch of the Royal Aeronautical Society in 1953 and in 1956 he was elected President of the Australian Division of the Society. He was also a most active and enthusiastic member, or delegate rather, of the Commonwealth Advisory Aeronautical Research Council, a body to which he referred in the paper and which came into existence in 1946.

Mr. Coombes joined the Royal Aircraft Establishment in the Aero Department in 1924 and a year after transferred to the Marine Aircraft Experimental Establishment at Felixstowe. He was recalled to Farnborough in 1930 to take charge there of the seaplane testing tank which had just been erected and many would remember that Mr. Coombes and the late Mr. W. G. A. Perring worked side by side on that tank for many years. He thought it was about 1938 when he and his family left England when there were no facilities at all in Australia for aeronautical research. Indeed there was no organisation in Australia for aeronautical research and he thought that there was no need personally or professionally for Mr. Coombes to go to Australia because he had already assured for himself an eminent aeronautical career in the British Air Ministry. Mr. Coombes therefore was just as much a pioneer, aeronautically speaking, as those men of sail who set out from England two centuries before him. Mr. Coombes was both architect and designer of the Aeronautical Research Laboratories in Melbourne and was now the leader there of a strong team of scientists and engineers who had made quite a reputation in the aeronautical sciences for the high quality of their work.

He would like now to read a message from Australia from Mr. Isbister, the honorary secretary of the Australian Division, which said: "Please convey to our President, Mr. L. P. Coombes, best wishes for a successful British Commonwealth and Empire Lecture. From Council and members of the Australian Division."

## Introduction

When I was invited by the Council of the Royal Aeronautical Society to deliver the British Commonwealth and Empire Lecture for 1956, I was deeply gratified. In accepting the honour, I was conscious of the importance of the occasion, but what I had not realised was the magnitude of the task of preparing a worthy lecture. In trying to present a broad picture of aeronautics in Australia, I found time to be my greatest enemy in the work of gathering information about fields other than my own. I must therefore ask for indulgence if my contribution falls below the standard set by my eminent predecessors.

In considering the scope of the lecture, I felt that there were two main aspects; firstly, the development of aeronautics in Australia itself; and secondly, the value, or possible future value, of this to the whole British Commonwealth. This train of thought had its beginnings ten years ago at a Commonwealth Aeronautical Research Conference in London. Sir Ben Lockspeiser, addressing the Conference, asked the Dominion representatives for a waterfall and a desert. These picturesque terms represented a genuine desire on the part of the United Kingdom to establish large scale communal testing facilities for the British Commonwealth of Nations. The waterfall was to supply power for a large supersonic tunnel, requiring up to half-a-million horse power for its operation. The desert was a large uninhabited tract of country in which experiments on supersonic aircraft and missiles could

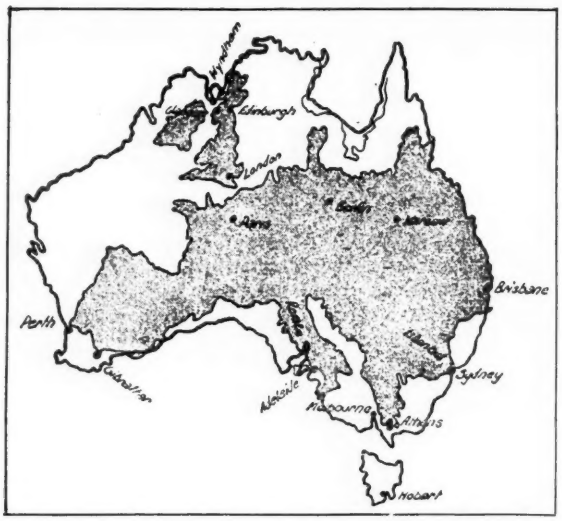



FIGURE 1. Comparative size of Australia and Europe.

be made in good climatic conditions and without danger to innocent third parties. The supersonic tunnel proposal came to naught but, as you all know, the Rocket Range at Woomera in Central Australia is an accomplished fact, and is already the finest testing ground of its kind in the world.

It is not at all convenient for the United Kingdom to use a range 12,000 miles away, but the advantages of climate and topography and of drawing upon local resources of scientific and technical manpower are so great that the decision to establish this joint project was pursued with vigour. This is an example which might well be extended into other spheres of aeronautics.

The salient characteristic of the country is that all the natural features encourage air operations; in fact, certain areas like New Guinea are being developed entirely by air transport. Thus, Australia is particularly suitable for the intensive flying of aircraft. In addition, we find efficient and experienced operators, a modern aircraft industry for maintenance or modification, and research laboratories for consultation and laboratory investigations. Many United Kingdom firms now have branches in the country. Thus, Australia could well become the testing ground for the British Commonwealth for aircraft as she has for guided weapons. She is a strongly pro-British member of the Commonwealth and has a great desire to strengthen it by helping to keep British aircraft in the forefront of progress.

I believe that Australia can play a much greater part in the aeronautical progress of the whole British Commonwealth if her natural advantages and resources are more widely known and utilised. I hope that my lecture will serve to inform other members of the Commonwealth of her achievements and potentialities in aeronautics.

I am indebted to the Chief Scientist, Department of Supply for permission to publish this paper. I must also acknowledge the assistance of a number of persons who have helped me in the preparation of material. I have tried to thank some of them by name at the end of the text.

TABLE I

INTERNAL AND DOMESTIC SERVICES

| | *1944* | *1955* | *Ratio* |
|---|---|---|---|
| Miles Flown | 10,614,250 | 45,449,000 | × 4·5 |
| Passengers Carried | 241,863 | 2,041,013 | × 8·5 |
| Freight Carried | 1,729 tons | 82,774 tons | × 48 |
| Mail Carried | 2,437,858 ton/mls.* | 1,506,363 ton/mls. | × 0·62 |
| No. of Aircraft in Operation | 48 | 124 | × 2·6 |
| Miles of Route Open | 22,544 | 87,986 | × 3·9 |

*Includes amounts of Troop Mail carried long distances.

## Civil Aviation

The greatest development in aviation in Australia has occurred in the civil transport field. It is unnecessary for me to give any historical introduction, because that was done most ably by Sir Hudson Fysh in the First British Commonwealth Empire Lecture in 1946[1]. Sir Hudson described the pioneering days and beginnings of air transport and showed by statistics how the activity had grown over the years, illustrating this by a number of figures and tables. In the ten years which have elapsed since his lecture, the trends have been fully maintained. The Table on page 57 of his paper is set out in Table I. The figures for 1955 are included for comparison, together with the ratio of the two values in each case.

It will be observed that the growth factor varies from 2·6 to 48, which may well be regarded as a cause for satisfaction as the population during the same period has increased by a factor of about 1·3. Fourteen airlines are now operating of which the largest are: —

Australian National Airways Pty. Ltd.
Ansett Airways Ltd.
Butler Air Transport Ltd.
Guinea Airways Ltd.
MacRobertson Miller Airlines Ltd.
Qantas Empire Airways Ltd.
Trans-Australia Airlines.

There has been a steady development of the internal air services. Three diagrams have been drawn to show this and refer to the major air routes carrying between 1,000 and 10,000 passengers per week, those between 100 and 1,000 passengers, and the minor and outback services carrying less than 100 passengers per week. To give scale, a map of Europe has been drawn within the outline of Australia. In the external services the only striking change which would be seen in the diagram which Sir Hudson included is the Australia-Johannesburg link via the Cocos Islands. When one considers that maintenance of the present route via Singapore and the Middle East is entirely dependent upon the goodwill of nations no longer within the British Commonwealth, the strategic and commercial value of this link is clearly enormous. Incidentally, the over-water sections—Darwin-Cocos (2,284 miles) and Cocos-

TABLE II

| *Country* | *Population Millions* | *Pass. Miles per Head* | *Total Ton Miles/Head* |
|---|---|---|---|
| Australia | 8·908 | 111·7 | 5·98 |
| U.S.A. | 161·026 | 127·4 | 3·07 |
| Netherlands | 10·551 | 80·2 | 3·47 |
| Canada | 14·998 | 67·3 | 1·43 |
| U.K. | 50·926 | 29·8 | 1·09 |

Mauritius (2,683 miles) are among the longest in the world. Clearly the wartime experience of Qantas in flying between Perth and Colombo has been of considerable value.

Sir Hudson was a little disturbed by the threat that a Government airline would be formed and that it might compete unfairly against private enterprise. The issue was obviously a highly contentious one. However, many of the fears of the private companies proved unfounded and at the moment Trans-Australia Airlines, the Government airline, competes on equal terms with several commercial airlines. T.A.A. has proved a formidable competitor and a most efficient organisation. It has had an extremely stimulating and beneficial effect upon air transport in Australia.

The present position is that as a nation, Australia is one of the most air-minded in the world. This is shown by Table II, published by the Tenth Assembly Meeting of I.C.A.O. in June 1956.

These figures are on a per capita basis and in order to show the actual values of the traffic, two graphs have been plotted showing passenger miles and ton-miles of freight in comparison with United Kingdom figures. In each case the figures relate to the total of both internal and external airlines. It will be seen that Australian airlines are comparable in size with United Kingdom scheduled airlines, as they carry 55 per cent of the passenger load and about the same freight. As these graphs are actual figures, the extent to which Australians use air transport can be seen. The growth over the years is rapid and shows no signs of reaching a peak.

Australian fares are also the lowest in the world. This is shown by the following Table compiled by Aviation Studies Ltd. in their publication "An Examination of World Air Fares per Mile," October 1953. This shows that Australian fares are approximately half, or even less, than corresponding European fares, and also considerably below fares in the U.S.A.

*AIR FARES*

| *Internal Routes* | *Pence per mile (stg.)* |
|---|---|
| Australia | 3·6 |
| United States of America | 5·3 |
| Europe | 8·1 |
| Canada | 6·3 |

The fares on the overseas routes Australia operates are not much higher: —

| *International Routes* | |
|---|---|
| Sydney-London | 5·2 |
| San Francisco-Sydney | 7·1 |
| Sydney-Johannesburg | 6·0 |

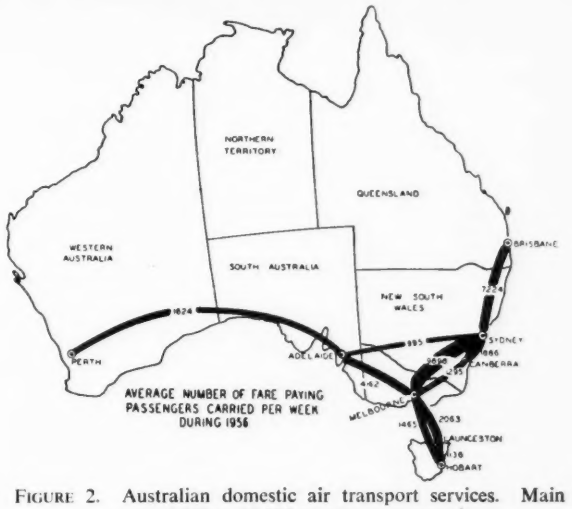



FIGURE 2. Australian domestic air transport services. Main routes 1,000 to 10,000 passengers per week.

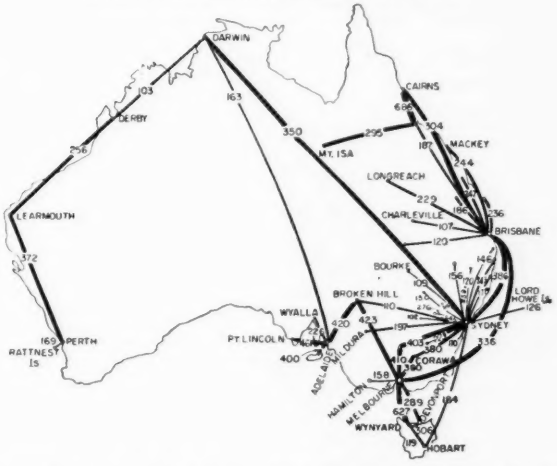



FIGURE 3. Australian domestic air transport services. Minor routes 100 to 1,000 passengers per week.

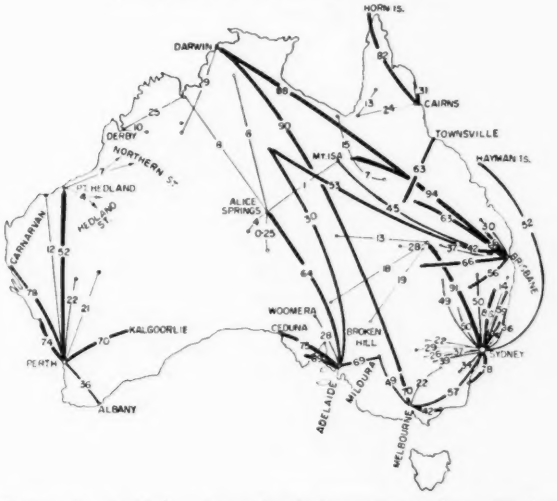



FIGURE 4. Australian domestic air transport services. Feeder and outback routes with less than 100 passengers per week.

TABLE III

UTILISATION OF CIVIL AIRCRAFT IN AUSTRALIA

| *Aircraft Type* | *No. of Aircraft on which figures are based* | *Average No. of Years in service* | *Average Total No. of Hours Flown* | *Average Utilisation Hours per annum* | *Greatest Average Utilisation Hours per annum** | *Maximum Hours Flown by any Aircraft* |
|---|---|---|---|---|---|---|
| DC-3 | 36 | 14 | 27,800 | 2005 | 2850 for 11 years | 47,100 |
| DC-4 | 16 | 11 | 29,050 | 2640 | 3615 for 10 years | 36,200 |
| Bristol Freighter | 3 | 10 | 12,650 | 1270 | 1350 for 10 years | 13,500 |
| DC-6 | 2 | 9 | 23,600 | 2630 | 2680 for 9 years | 24,000 |
| DC-6B | 2 | <2 | | 3440† | | |
| Convair 240 | 5 | 9 | 18,200 | 2140 | 2230 for 9 years | 20,100 |
| Convair 340 | 2 | 2 | | 3315† | | |
| Viscount | 5 | <2 | | 2940† | | 3,280 |
| Constellation | 7 | <2 | | 2505† | | 4,030 |
| Dove | 5 | 8½ | 10,400 | 1210 | 2040 for 9 years | 18,400 |

*Figures refer to the aircraft with the highest average utilisation during its whole life.

†In these cases the type has only recently been introduced and the mean utilisation for the whole fleet during 1955 has been given.

While comparison on a monetary basis is a little misleading, since in the U.S.A., for example, passengers can afford a much higher fare, Australia is handicapped in having to import her aircraft, spares and fuel from other countries so that costs are loaded against her. On the other hand, a comparison on a purchasing value basis with Europe is even more favourable to Australia.

A feature of civil air transport in Australia has been the extraordinarily high utilisation of aircraft. Table III shows examples of the hours flown by various aircraft types in current use. In each case the figures are the mean for the whole fleet and can be regarded as typical.

The large passenger aircraft have utilisations of between 2,000 and 4,000 hours per annum, continued for periods of 10 years or more, the average being about 3,000 hours per annum. Small passenger aircraft which operate on feeder lines, and freighters, have lower utilisations. This is not a reflection on the serviceability of the particular types but of the kind of service on which they are engaged. Total lives, too, are becoming great and some of the DC-3 aircraft, which have seen the longest service of any type in use, are approaching a life of 50,000 hours. Loads, too, are very satisfactory. The overall load factor for all airlines is 63 per cent, while the highest load factor, 71 per cent, has been obtained on the Viscount fleet.

High utilisation has not been achieved at the expense of safety. Fig. 7 has been drawn for the past ten years of passenger fatalities per 100 million passenger miles for three countries—the United Kingdom, U.S.A. and Australia. The yearly values tend to fluctuate widely and, to show trends, a smoothing process has been applied, each year's value being the mean of three years. The graphs show that since 1951 Australia has had the lowest fatality rate.

One result of this intensive utilisation is that Australia is a good testing ground for civil aircraft. A second result is that the civil operators in Australia have encountered the phenomenon of structural fatigue earlier than has been the case in other countries; the particular aircraft types have often first reached the dangerous age in Australia, and this experience has been dearly bought. This fact was recognised many years ago and intensive research put in hand.

The growth of air transport and the high utilisation of aircraft in Australia are due to a combination of a number of causes. First, we have the energy and enterprise of the operators. I am sure that Sir Hudson Fysh's lecture gave an adequate impression of this. A second major factor is the favourable climate, topography and distribution of centres of population. Our large cities are distributed on a roughly peripheral pattern, which is clearly seen in the map of the major air services already given in Fig. 2. In other countries such as the United Kingdom, the pattern tends to be radial from the centre of operations. The peripheral pattern allows aircraft to fly from stage to stage around the perimeter during the hours in which passengers are prepared to travel, and the aircraft stops at the last one reached for the nightly overhaul. It does not necessarily have to return to a central base, and any

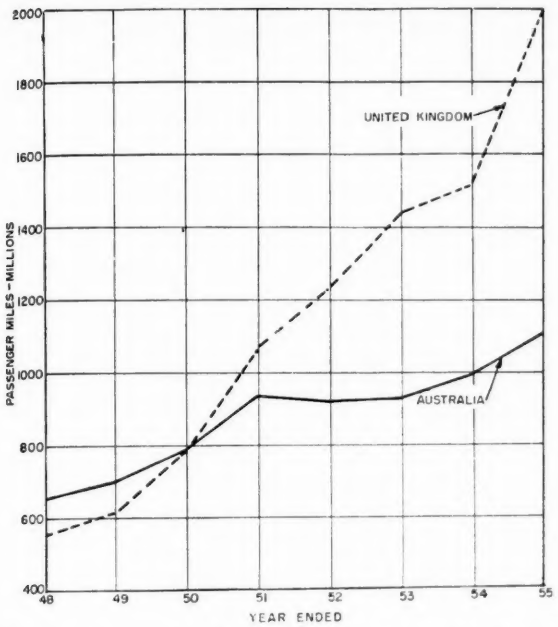



FIGURE 5. Comparison of regular public transport operations. Total passenger-miles for both internal and external airlines.

new and faster type of aircraft introduced merely means that more stages are covered and the aircraft stops at a different point, but it can be operated just as efficiently. In the radial pattern, increases in speed of aircraft cannot be efficiently utilised unless the aircraft can make a complete extra return journey. The minor and outback routes in Australia tend to the radial pattern. This can be seen from Figs. 3 and 4.

Another factor in the efficiency of Australian airlines is the unrestricted competition which is allowed and, indeed, cannot be prevented on inter-State routes under the Constitution. This forces operators to be bold and progressive in the choice of equipment and to buy from the country producing the best types. Thus, the airlines have bought both British and American aircraft, and at the moment Dutch and French types are under serious consideration. There does not seem to be the same degree of competition in other parts of the world. In Europe there is a Revenue Pooling Agreement between British and Continental carriers, and in America the Civil Aeronautics Board is charged with maintaining the health and sound economy of the air transport industry. It must issue a certificate of fitness and necessity before an airline can operate on any particular route, and in this way no uneconomic competition is allowed. In contrast, on the Melbourne-Sydney route four airlines are in operation and no one can prevent more from entering the fray.

The low fares charged by Australian airlines are a result of this free competition. Apart from competition between airlines, the railways carry passengers at fantastically low fares which are quite uneconomic and far below rail fares in other countries. One limitation on this particular form of competition is that the number

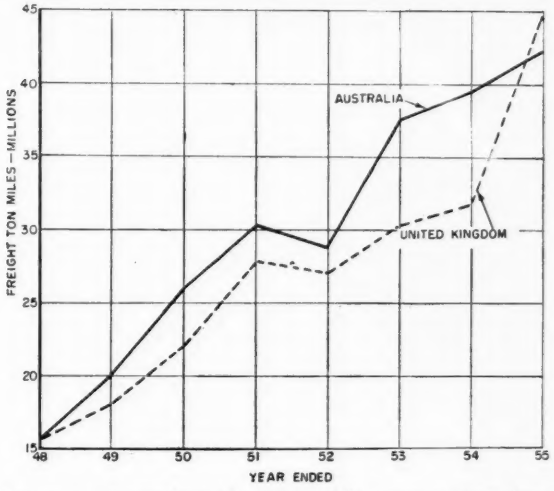



FIGURE 6. Comparison of regular public transport operations. Total ton-miles of freight for both internal and external airlines.

of passenger seats available on trains and inter-State buses does not meet the demand. Between Melbourne and Sydney we find the following number of passenger seats available in each direction per week: —

| | |
|---|---|
| Rail—1st and 2nd Class | 2,923 |
| Road | 980 |
| Air | 6,864 |

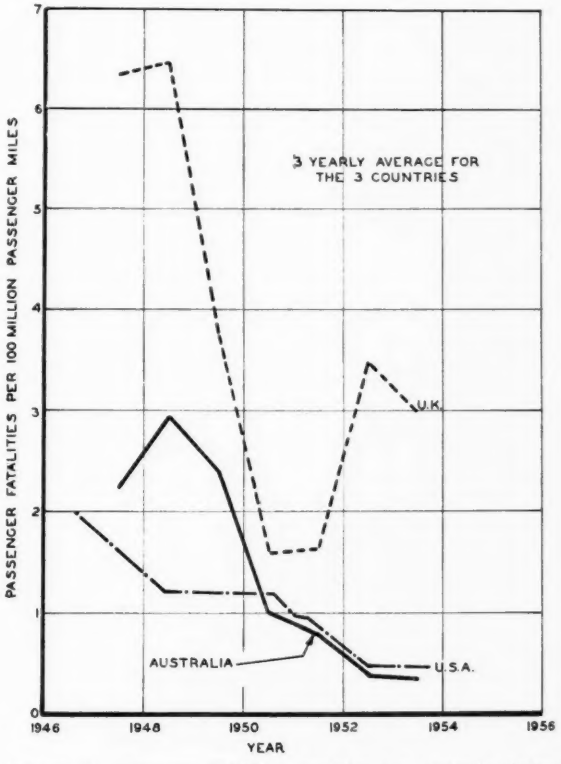



FIGURE 7. Passenger fatalities—statistics for Australia-United Kingdom-United States.

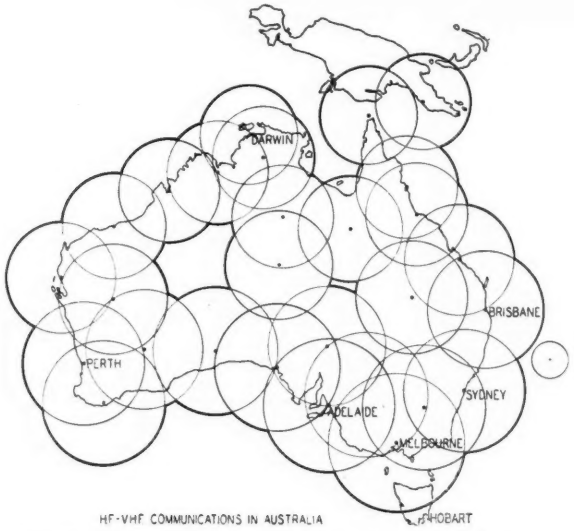



FIGURE 8. Radio telephone communications in Australia.

This particular run is the busiest, and the figures between other capital cities would not show such a striking comparison. On the long run to Perth there would be more rail passengers than air, but to Tasmania, where the boat service is extremely poor, the air services carry the great bulk of the passengers.

A significant factor in the growth of Australian air travel is the possibility of commuting between the cities. A business man, travelling by air between Melbourne and Sydney, or Melbourne and Adelaide, can do almost a full day's work and return the same day. Non-stop flights have also been introduced between Melbourne and Brisbane, Sydney and Adelaide and Adelaide and Brisbane, the distance by surface transport being over 1,000 miles in each case. By air, it is possible to spend four or five hours in one city and return the same day.

FIGURE 9. Radio range system in Australia.

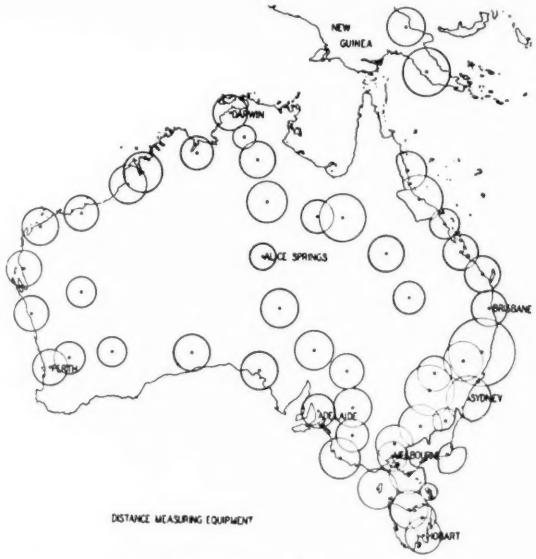



FIGURE 10. Distance measuring equipment beacons.

This is, of course, a big encouragement to travel by air rather than by surface transport.

Yet another factor encouraging the growth of air transport is the favourable attitude of the Commonwealth Government as expressed through the Department of Civil Aviation. There is a reason for this, quite apart from the obvious need to develop the backward parts of the country. A strong civil air transport system is regarded as an insurance of great value in times of emergency, and during the last war, the airlines in Australia were able to provide aircraft, pilots and experience of vital use to the R.A.A.F.

The Department of Civil Aviation has a dual function. Firstly, it is the regulatory body and must ensure adequate standards of safety; secondly, it develops and provides the ground facilities which are indispensable to a modern air transport system. The extent of the developments in navigation aids can be gauged by three diagrams which have been reproduced as Figs. 8, 9 and 10.

It will be seen that the pilot is well catered for. He is always in radio communication with a ground station and is guided by radio paths over most of the length of any particular flight. Moreover, he knows his exact distance from key points. The navigational and communication facilities are not bettered anywhere else in the world; in fact, distance measuring equipment has been in large scale use in Australia for many years before being introduced elsewhere. The particular form of this equipment which was developed by the Radio Physics Laboratory of the Commonwealth Scientific and Industrial Research Organisation, in association with Amalgamated Wireless of Australia Limited, is still regarded as the best of its kind.

Airports have been consistently improved and there are now some 200 Government and 300 privately owned airports in Australia, classed as follows:—

| | |
|---|---|
| Suitable International Airliners (*e.g.* DC-6, Constellations) | 8 |
| Suitable Viscount | 23 |
| Suitable DC-3—all weather | 67 |
| Suitable DC-3—dry weather only | 149 |
| Others | 236 |
| Total | 483 |

In addition there are about 150 aerodromes and airstrips in New Guinea.

The Department of Civil Aviation encourages the general development of the country by the provision of airport and navigation facilities. However, in New Guinea, many parts of which are quite uncivilised, the Department is taking a particularly active part in the development of the inaccessible and backward areas.

FIGURE 11. Working party in New Guinea ready to consolidate an airstrip.

## Air Operations in New Guinea

New Guinea has had a long record of development by the use of the aeroplane. In the 1920's the gold fields at Bulolo were almost entirely developed by air transport, using Junkers Ju. 52 aircraft. Every piece of heavy dredging machinery was carried over the mountains from Lae, and the tonnage of air freight carried in New Guinea during this period was a world record at the time. Air transport continued to play a great part until the war, when all civil operations ceased and the Japanese occupied many parts of the island.

Since the war, air transport has assumed its vital role in this area and it is no exaggeration to say that the country is being developed almost entirely by the use of the aeroplane. In this work, the Department of Civil Aviation is playing a leading part by establishing extensive facilities in the shape of airfields, communication and weather forecasting services. Further, it exercises a most careful control over flying operations. Certain coastal areas are well advanced and white and Asiatic settlers are established freely. On the other hand, the mountains and plateaus of the interior are still far from being civilised, and it is extremely dangerous for strangers to mix with the primitive tribes until a sympathetic contact has been made by experienced administrators, who gradually accustom the tribesmen to the white man's ways. As an example, the wheel is unknown, and the natives refuse to push wheel-barrows; they carry them! Similarly, they will not use rollers to consolidate airstrips. Instead, suitable refreshments are provided and the natives stage a war-dance in which

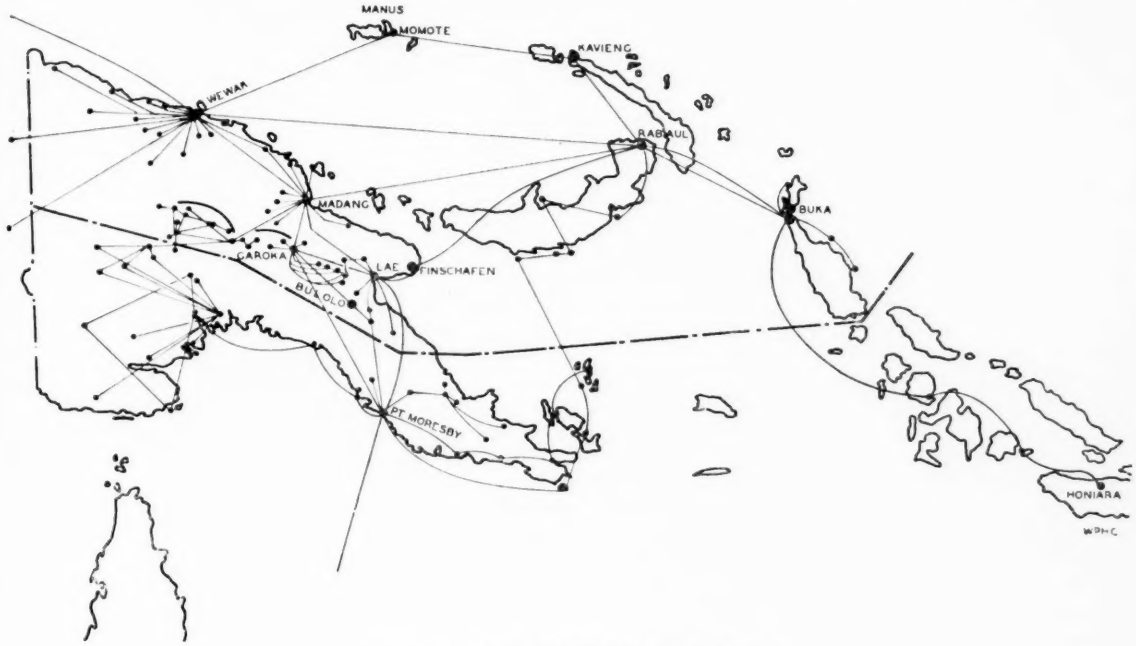



FIGURE 12. Air routes in New Guinea and Papua.

FIGURE 13. Airstrip built on a mountain slope in New Guinea.

3,000 to 5,000 warriors in full regalia stamp up and down the airstrip for two or three days. No strangers are allowed into these new or "uncontrolled" areas without passes, which are not granted to any but completely suitable persons.

In this civilising work, the aeroplane is the chief vehicle. When an area is to be brought under control aerial surveys are made to establish accurate maps and give data on the possibility of land communications and suitable sites for air strips. The population of the area is estimated by counting the habitations. A Government patrol will then set up its headquarters at a place where it can be maintained by air. At first, supplies will be dropped and later an air strip constructed for light aircraft. In this manner, no less than 150 airfields and airstrips are to be found in New Guinea and its islands. Fig. 12 shows some of these airfields and the extensive network of air routes. There are also 300 helicopter landing grounds. These craft are used extensively by the oil exploration companies.

Licensing of pilots is rigorously supervised, because the flying conditions are far from ordinary. Heavy cloud builds up during the day and the dense vegetation and mountainous topography make the construction of airstrips difficult. I.C.A.O. standards simply cannot be observed. Airstrips are often not level and in cases the slope may approach one in eight; the pilot takes off downhill and lands uphill. Most of these sloping strips face into a mountain side so that the pilot has no second chance and must land on his first approach. Other strips are built on a curve because there is not sufficient length of straight run. Again, the density altitude is far from standard. There are plateaus with an elevation of 5,000 ft. and a temperature of 30° to 35°C. Under I.C.A.N. standard the temperature should be −4°C. These hazards mean that pilots must be familiarised very carefully and, in fact, they are not allowed to use some of the more difficult airfields until they have had over 1,000 hours flying in New Guinea. Helicopter landing grounds are often clearances in the jungle 100 ft. wide by 300 ft. long. The length is to allow the machines to fly up and down the cleared space to gain height on a zig-zag course, as owing to the density altitude they cannot climb vertically.

The aircraft in use vary from fairly light aircraft, which must be used because of the poor aerodromes, to

FIGURE 14. Curved airstrip cut in New Guinea jungle (left side unusable due to Japanese bomb craters).

aircraft like DC-3s and Hudsons which serve the major routes. A number of flying boat services also loop around the coast and to the various islands.

The subject of flying in New Guinea would warrant a lecture in itself, but I have said sufficient to show how great a part the aeroplane is playing in developing this backward part of the Australian territories.

## Air Freight

Air freight in Australia is quite a large business. The actual ton-miles of air freight carried within Australian territories during 1955 was 53,180,000, which makes Australia the third greatest air freight carrier in the world. On a per capita basis, she ranks first. Despite this, there are two different schools of thought on air freight. On the one hand, the conservative operator argues that with present designs of freighter, direct operating costs are 1/- (Australian) per ton-mile. Allowing for overheads, and the fact that backloadings are generally light, the cost of air freight is about 3/- per ton-mile, which is the average rate charged. These operators therefore make air freight secondary cargo which fills in the loads on the passenger services. The advocates of air freight, chief among whom is Mr. I. Grabowski, Development Manager of Australian National Airways, do not dispute this reasoning, although they believe that larger and more efficient freighters would reduce the direct operating costs. This in turn would put up average loadings so that overall ton-mile costs might even be halved. However, their main contention is that direct operating costs are misleading in making comparisons between surface and air transport and that factors such as speed of delivery, cost of handling, packaging against damage or dust, heavy vibration on bad roads, and many others, favour air transport even when there is an existing and adequate rail or road system. Aeroplanes show to advantage when surface transport is poor. Between the Australian mainland and Tasmania and the smaller islands, air freight is extensively used. Thus, 200 cars per month were being air freighted to Tasmania, and the ratio of farm animals being sent by air and by sea

is approximately ten to one. Density of cargo is also a factor in ships, as freights are charged by the cubic ton and not by weight. With light cargoes which occupy more than 4 or 5 cubic tons per ton weight, air freight is cheaper, and hence, one finds that furniture, clothes, boots and shoes are sent by air.

Air freight can play an important part in the development of outback country[2]. In the more highly developed parts, roads and railways exist and their initial cost has already been met. If new country is to be opened, an all-weather road costs £15,000 per mile and a railway far more. Until the volume of traffic on such highways is large, the real total cost per ton-mile by surface transport is great. This fact is often concealed by not charging economic fees for the use of the permanent way. On the other hand, air transport initially makes light demands. Landing grounds for feeder line or freight work are cheap and the capital charges per route mile are therefore quite small. Primary produce cannot pay charges of 3/- per ton-mile, but a subsidy to halve this is a small price in comparison with building roads or railways. Moreover, if the venture is not a success, it can be stopped without wasting enormous capital sums. If the area develops and traffic grows, roads can be built as soon as it is clear that the traffic will justify the expense. Such a venture is Air Beef, an inland killing centre at Glenroy in the Kimberley cattle country of Northwest Australia. Cattle in the neighbouring stations no longer walk hundreds of miles to market with losses in numbers and condition. They are killed locally and flown to the chilled stores in Wyndham for export by sea, or to be sent by rail to Perth. Younger animals and many which would not survive a long trek can be sent to such a local killing centre. Thus both quality and quantity improve, as Fig. 15 shows. Besides, a local industry builds up around the meat works and the station owners can afford to import fencing, implements, fertilisers and other items which improve the back loading.

Some say that this picture is artificial and would collapse without a subsidy, but can one really estimate the national value of these imaginative ventures? Another example, and not an impossible one, is grazing on the mountain slopes in the Snowy Mountains Hydro Electric Scheme—a colossal development in power and irrigation. The graziers have been told to leave as they cause soil erosion. If these pastures are improved by top dressing, which can only be done from the air, this menace may be overcome and thus productivity of the area maintained. Once again, the sheer economics of the scheme may kill it, whereas the national contribution may well justify a subsidy. My own strong feeling is that we need more of this sort of pioneer spirit and imaginative thinking if the outback of Australia and other undeveloped parts of the British Commonwealth are to realise their full potential value.

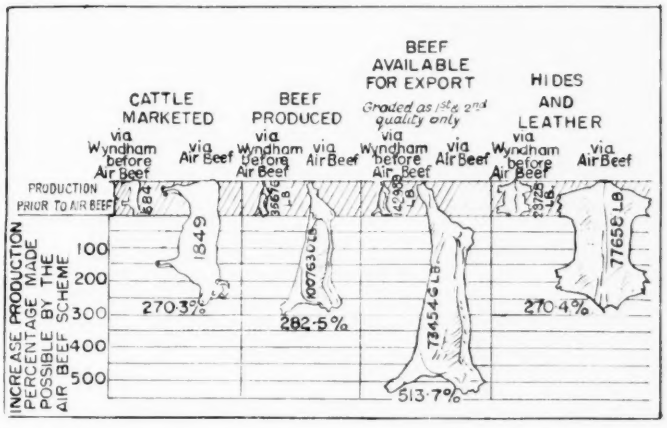



FIGURE 15. Improvement in beef production due to air transport.

## Agricultural and Other Civil Flying Operations

There are other ways besides transport in which the aeroplane has been used to develop Australia. The Flying Doctor Service has been widely publicised and aeroplanes have been used to make mineral surveys; in particular to seek uranium.

Helicopters are only just being brought into use, but already many applications for which they alone are suitable have been found.

Greater progress would be made in agricultural flying by the availability of suitable aircraft at the right price. In New Zealand, aerial top-dressing is the only method of bringing mountain areas into use, but in Australia the flatter terrain makes surface transport methods comparable or lower in cost. Nevertheless, the use of the aeroplane in agriculture is increasing. In the better rainfall areas top dressing with superphosphate alone, or with seeding, enables pastures to be developed quickly, particularly where the use of ground machinery is difficult owing to the steepness of the terrain, or because of surface obstructions such as rocks or fallen timber. This applies to areas of New South Wales, Victoria and Tasmania which total about 5 million acres.

In Queensland there are large areas where superphosphate is not needed and pastures may be developed for the low cost of aerial seeding. In this State, one of the most attractive uses is in country over-run by brigalow scrub. This pest is associated with areas of high fertility and satisfactory rainfall, but the dense scrub renders them practically useless. The area so affected has been estimated at 14 million acres. However, the scrub can be destroyed by spraying with hormone herbicides which are effective at very low rates of application. The only practicable way of applying these sprays is from the air, and already significant areas have been treated. The scrub can be cleared mechanically with heavy tractors at a cost of 35/- per acre as compared with 45/- for aerial spraying, but the time taken by air is much less. In the Roma

district the carrying capacity of the land was raised from nothing to one sheep per acre within a year, which made the operation clearly worthwhile.

Crop protection by aircraft is comparatively neglected, although it has advantages. There is no damage to the growing crop, a particularly valuable feature in tall-growing crops such as tobacco. Now that powerful chemicals effective at low rates of application are available, aerial spraying operations are becoming competitive with the cost of ground spraying with the inherent advantages of speed and absence of damage.

Brief mention should be made of the use of aircraft in Australia for the control of noxious weeds such as the Bathurst burr; the dropping of poison bait for the destruction of wild dogs, dingoes and rabbits; and the control of swarms of plague-locust. In such cases aircraft have proved themselves, particularly in sparsely populated and remote regions or where the points of operation have been widely scattered.

The following statistics refer to aerial operations during the 9 months ending 31st March 1956:—

| | | |
|---|---|---|
| Superphosphate | Weight | 19,348 tons |
| | Area | 330,564 acres |
| Insecticide & Herbicide | Area | 397,446 acres |
| Seed | Weight | 64,155 lb. |
| | Area | 50,280 acres |

These figures exclude the special attack on the Victorian plague locust in which the R.A.A.F. and T.A.A. sprayed 220,000 acres of pasture.

The hours flown on agricultural work have increased rapidly over the past three years, the actual figures being:—

| | |
|---|---|
| 1953 | 5,000 hours |
| 1954 | 10,600 hours |
| 1955 | 20,900 hours |

However, this increasing use of aeroplanes is mainly due to the convenience and speed and not to the economy of the operations. Any recession in prices of farm produce might force a large reversion to conventional ground methods.

About 98 aircraft are registered for operation solely on agricultural work. After study of overseas operations, design requirements for agricultural aircraft have been drafted and proposals made for an agricultural over-load where there is no third-party risk. While in theory this should improve operating economy, in practice it is likely to legalise a procedure which operators have been employing for some time. This has happened in New Zealand where, in spite of concessions, operators are still one jump ahead of the regulation weight.

While agricultural work tends to be seasonal the effect of this is reduced to a large extent by making the installation in the aeroplane easily convertible from, say, top-dressing to spraying and vice versa, and by taking advantage of the wide range of latitude through which the Australian Continent extends (from the southern tip of Tasmania to Cape York is 2,300 miles), the "season" can, within certain economic considerations, be followed in its passage up or down the Continent.

## Private Flying

Private flying as a means of transport has not made great progress in spite of the fact that climate and topography favour it. In this regard, Australia is far behind the U.S.A. and Canada. In the U.S.A., for example, there may be up to twenty aerodromes around a large city. Memphis, with a population of half-a-million, has nine airfields, while Sydney and Melbourne, with three times the population, have each only two. The American will find all kinds of facilities at the airports including drive-yourself hire cars, whereas the Australian owner finds very primitive arrangements for his convenience.

The two main factors hindering the growth of private flying are the excellence of the commercial air services and the high cost of aeroplanes which suit Australian conditions. The well developed network of feeder routes throughout the whole of Australia discourages the private owner. A station owner, wishing to visit a large centre of population would not have to travel more than about 50 miles to the nearest landing ground visited by a regular commercial airline. Here, with no trouble to himself and great safety, he can fly to a capital city, whereas at certain times of the year, such as in the wet season, private flying can be extremely dangerous. These feeder lines are being continuously extended in Australia and some of the ports of call are little more than sheep stations or very small hamlets. Cornellan Airways, for example, flies regularly over 10,000 miles of unduplicated routes in the sparsely populated North-West.

For the private aeroplane to compete with the great advantages of flying by commercial airlines, it needs to have a good performance, and cockpit comfort and appointments approaching that of the average saloon motor car. Electric starting is essential and some form of radio. Available British aircraft are in the right price bracket, but generally, their performance is rather poor in Australian climatic conditions. A minimum acceptable performance in temperate conditions would be 1,000 feet per minute climb, at least 150 m.p.h. cruising speed and a range of 500, or preferably 1,000, miles. There are American aircraft available which measure up to these standards of performance and cockpit comfort, but the price is far too high.

Similar factors limit to a mere handful the executive type aeroplanes which are extensively used in the U.S.A. In Australia, industry is localised and close to the large centres of population which will certainly have a main line airport. Thus, the business executive has perfectly convenient commercial air transport and the advantages of the private aeroplane are largely nullified. In America, industry is scattered over the whole Continent, and quite important factories are often found in small towns, so that the executive type of aeroplane has very real merits. Once again the only suitable small

executive type aeroplanes are American, and the price is usually high and has to be paid in hard currency.

Just after the war there was a third adverse factor—over-regulation of flying—but this has been corrected. Before the war there was little need for control and flying was becoming popular as there was considerable freedom in the use of the aeroplane. All private flying was suspended during the war, and although there were cheap aeroplanes available from disposals when it was over, there was also a great increase in the number of regulations imposed by the Department of Civil Aviation upon all kinds of flying. Commercial flying was expanding rapidly, and the regulatory arrangements were designed primarily to ensure the safety of fare-paying passengers. As a consequence, the private owner and light commercial operator were so harried that the whole object of flying, which was to be free of the confines of the earth-bound mortal, was lost. An Aircraft Owners and Pilots Association was formed in 1948 with the object of collective bargaining with the Department of Civil Aviation. Over the years, it has succeeded to a considerable measure, and the Department has now a very tolerant attitude to the private owner. As an example, under the new regulations, maintenance of aircraft in Australia is probably cheaper than in any other country, because private owners are now allowed to do the bulk of routine maintenance themselves and only inspection and major repairs must be done by licensed personnel. Only last April a Symposium was arranged between private owners and the Department to discuss the possibility of further concessions.

Private aircraft are not allowed to use the major civil airports unless they have radio, and the Department of Civil Aviation provides special aerodromes for light aeroplanes in Brisbane, Sydney, Melbourne, Adelaide, Perth and Hobart. Private aircraft may use other civil airports where the traffic is much less dense and aircraft without radio can be reasonably well controlled. Night flying is only allowed if the aeroplane has full instrument flight facilities; this is impractical in a light single-engined aeroplane. Regulations regarding controlled air space must be strictly observed, but apart from the areas round the airports, private aircraft have adequate freedom of movement as they can cross the aerial highways, provided that they keep below 1,500 feet near the airports and 3,000 feet elsewhere. All powered aircraft are, of course, subject to the airworthiness regulations of the Department.

All in all, it may be said that control of private flying in Australia is now as good as in any other country and not unduly restrictive.

## Club Flying and Gliding

Flying as a sport appeals to Australians and both light aeroplane and gliding clubs are numerous and healthy.

The Commonwealth Government was far-seeing enough to encourage the formation of clubs in the early 1920's, and in 1926 began a system of financial grants and assistance in kind. When the war broke out in 1939, this policy paid dividends as the clubs, with a fleet of some 70 aircraft, gave immediate assistance in the R.A.A.F. flying training programme. Cadets who were about to begin a course at Point Cook were transferred to the clubs, and the R.A.A.F. School undertook the intensive training of instructors, these being selected from instructors attached to clubs. Eventually, all club aircraft were impressed by the R.A.A.F., but the clubs had made an important initial contribution to the expansion of the Air Force.

After the war, the Cabinet actively assisted the re-establishment of the clubs and has continued the policy of grants for maintenance and replacement, and bonuses for licences. The licence bonuses are also available to commercial schools, but in every case are limited to persons in the age groups most useful to defence, *i.e. ab initio* pupils under 30 and trained pilots up to 38 years of age. This integration with Service needs goes farther and the R.A.A.F. and Army use the clubs and schools to train pilots; in fact, at present 12,000 hours per annum, or about one-sixth of the total club and school flying, is used for Service training.

At the present time there are 24 aero clubs and six commercial flying schools officially recognised in Australia. Club aircraft number 150, the majority being Tiger Moths, Austers and Chipmunks, and there are over 100 instructors employed. Since the war nearly 2,000 "A" licences have been granted and more than 6,000 renewed under the bonus scheme.

The cost of even light aeroplanes is beyond many enthusiasts and an Ultra Light Aircraft Association was formed in October, 1955. Divisions of this body have been formed in five States and two aircraft should be flying early next year. One will be an adaptation by Mr. H. Millicer of Melbourne of his light aeroplane design which won the Royal Aero Club competition of 1952. The Department of Civil Aviation has relaxed some of the normal airworthiness requirements for ultra-light aircraft to encourage the owner with limited resources. The Association already has over 200 members and this number will increase rapidly when aircraft become available.

The cheapest form of flying is gliding, and it is popular in Australia. Although the first glider flight was made in 1914, gliding did not really begin till 1929. Within a few years there were 15 clubs in Victoria alone, but the war reduced the number of active clubs to four or five. However, there has since been a steady growth and there are now 35 clubs in the Gliding Federation of Australia with some 900 active members. The number of gliders in use is about 70. Last year 17,000 launches were made for a flying time of 2,200 hours, and the number of launches this year will be between 19 and 20,000, while the time will exceed 3,000 hours. Applications for membership are so great that many of the larger clubs have had to close their membership temporarily.

Until recently nearly every glider developed in Australia was designed by an amateur. The first practical local glider was the "Golden Eagle", designed by H. G. Richardson and first flown in 1937. It is still

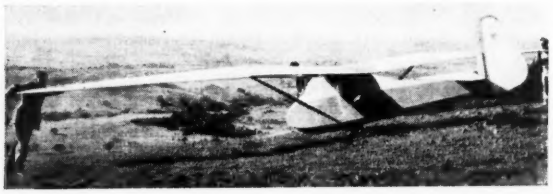


FIGURE 16. "Golden Eagle" glider built by H. G. Richardson in 1937.

FIGURE 17. E.S. 52 Kookaburra glider built by Edmund Schneider (1955).

flying after 19 years of regular use. The amount of home design and construction is appreciable. During 1955, four new designs were completed and flown and another five are expected to fly in 1956. This state of affairs is now changing with the establishment of two manufacturers; one is Edmund Schneider of Gronau fame. His E.S. 52 Kookaburra, of wood construction, is fast proving a suitable glider for club use. Table IV gives data on the performance of some Australian gliders.

Before 1949, a designer could please himself about strength requirements. Since then the Gliding Federation has adopted the British and American airworthiness requirements as a guide, and administered them without having the legal authority. This arrangement has worked satisfactorily and no accidents due to structural failure in flight have occurred in the past seven years. However, to give adequate legal powers to the Gliding Federation, the Department of Civil Aviation is now preparing Air Navigation Orders which will bring gliding under its control, with the power to delegate authority.

Most gliders are built of wood and this presents a problem to airworthiness authorities. In coastal regions, changes in moisture content cause expansion and contraction. In inland centres like Alice Springs, precautions will have to be taken to prevent large temperature rises while gliders are standing in the hot sun. The results of investigations[3] have shown that a temperature rise of 60°C, which is easily possible, causes a 50 per cent decrease in structural strength.

Australia is fortunate in having excellent examples of the three main sources of "lift," the essential requirement for soaring flight, namely, thermal activity, slope or hill lift, and the meteorological phenomenon known as "standing wave". While there are difficulties which prevent them from being fully exploited, we are not far behind world standards. A chart of distance records shows that Australians did not start this kind of flying until some years after the first overseas cross-country flight. There is quite a deterrent in Australia against making long flights as many areas although meteorologically suitable, are uninhabited and remote. A competition regulation in Australia ensures that each glider must carry a survival pack and certain areas are declared non-flyable to prevent pilots from endangering themselves. However, with the establishment of inland clubs at Mt. Isa and Alice Springs we are looking forward to capturing the World Distance Record in the near future, despite these deterrents.

I must now leave the subject of civil flying, but before doing so I should like to pay a tribute to the work of the Department of Civil Aviation. It has carried out its regulatory functions with wisdom and sympathy, maintaining a high standard of safety without discouragingly severe regulation of the operators. The airport and navigational facilities it has provided show foresight and imagination, and the Department is actively helping in the development of backward areas.

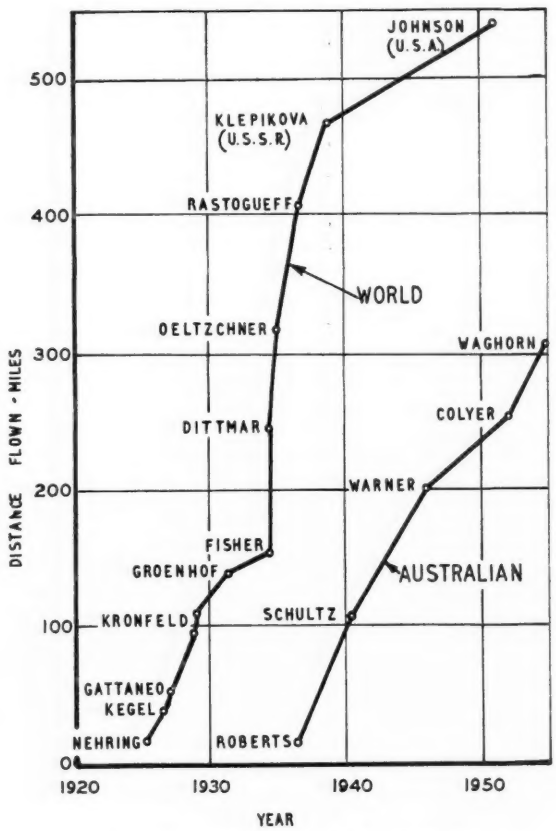



FIGURE 18. Distance records for gliders.

## The Aircraft Industry

Aircraft have been built in Australia for nearly fifty years as there is a record of G. A. Taylor (whose name is commemorated in one of the Society's medals) having established an aircraft factory in 1908. In the year following he persuaded the Commonwealth

TABLE IV

PERFORMANCE FIGURES FOR AUSTRALIAN DESIGNED GLIDERS

| *Glider* | *Span Feet* | *Weight lb.* *Empty* | *a.u.w.* | *Stalling Speed m.p.h.* | *Min. Sink f.p.s.* | *Best Gliding Angle* | *Wing Section* |
|---|---|---|---|---|---|---|---|
| Golden Eagle | 45 | 420 | 600 | 31 | 2·7 | 1 : 21 | Gö 535-Clark YH |
| E.S. 56 (Nymph) | 39 | 300 | 500 | 33 | 2·6 | 1 : 25 | Laminar |
| Swallow | 33 | 180 | 380 | 32 | 2·9 | 1 : 20 | N.A.C.A. 4415 |
| Joey | 32 | 140 | 280 | 30 | 2·4 | 1 : 24 | Gö 549 |
| E.S. 52 (Kookaburra) | 39 | 390 | 770 | 32 | 3·1 | 1 : 22 | Gö 549 |

Government to offer a prize of £5,000 for the best military aircraft produced to its requirements. The specification must have been somewhat ambitious as thirty years later no aircraft had yet been produced which fulfilled even the minimum conditions. Whether Taylor's factory produced any aircraft is not recorded, but in October 1910, J. R. Duigan flew in an aeroplane of his own design and construction, powered by an engine built by another Australian, T. E. Tilley. This was only a few months after the first aeroplane flight in Australia which was made by Harry Houdini, the escapologist, in a Voisin monoplane.

The first proposal to build aeroplanes in quantity was made in May 1918, when the critical situation in Europe caused the U.K. to ask Australia to build 200 aeroplanes. An Aircraft Construction Committee was appointed and this body chose the D.H. 9A to be fitted with the Liberty engine. Before the project had got beyond the stage of acquiring materials the war ended, but the Committee was so impressed with the difficulty of obtaining aircraft materials that it sponsored research in the Universities of Melbourne and Sydney into the suitability of Australian species of timber for aircraft construction. At about the same time the Australian Aircraft and Engine Company of Sydney built six Avro 504K's for the Department of Defence. These incorporated local materials of construction.

In 1924, the Australian Air Board established the Aircraft Experimental Station at Randwick, New South Wales to develop new designs of aircraft and new methods of construction. Wing Commander L. J. (now Sir Laurence) Wackett was placed in charge as he had attracted attention during the war by his inventions and ingenuity while serving in the Middle East War Zone. During the five years of its existence, the Experimental Station evolved five aircraft; the Warbler, a light aeroplane with a novel type of engine, in 1925; Widgeon I, a flying boat with a Nimbus engine; an amphibian version of Widgeon I and the improved amphibian Widgeon II; the Warrigal I trainer, and finally the Warrigal II trainer in 1929. Some excellent research was done in connection with these designs. However, financial stringency and other considerations caused the Air Board to close down the station.

There were other beginnings of the aircraft industry, such as the Larkin Aircraft Company of Melbourne, but none of these survived the economic blizzard of the depression of 1932. However, in 1936, Mr. Essington Lewis, the great Australian industrialist, visited Japan and what he saw convinced him that Australia faced grave danger. On his return, he was instrumental in forming Commonwealth Aircraft Corporation, a completely modern factory to build both airframes and

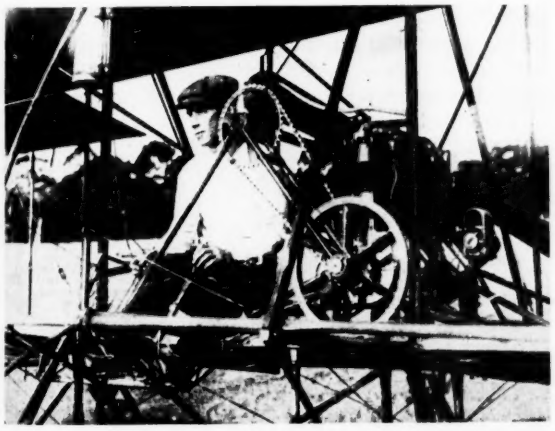


FIGURE 19. J. R. Duigan at the controls of first Australian-built aeroplane.

FIGURE 20. First Australian-built aeroplane in flight—October 1910.

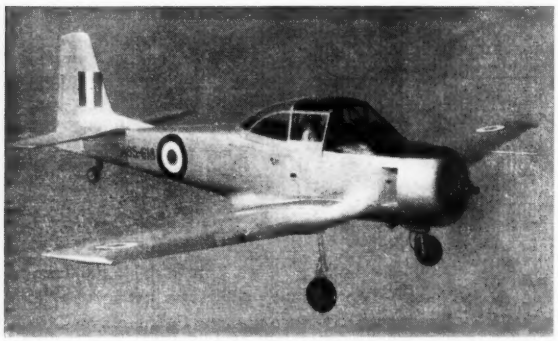


FIGURE 21. "Winjeel" primary trainer. (Commonwealth Aircraft Corporation, Melbourne.)

engines. The first type chosen was the North American type 33 trainer, known as the Harvard in England and Wirraway in Australia, together with the Pratt and Whitney Wasp aero engine. This combination proved to be the backbone of the Empire Training Scheme in Australia. It has been said that the training of air crew was one of the significant contributions of Australia in the war.

Wing Commander Wackett was appointed Manager and carried on the tradition of new aircraft development which had not been interrupted by the closing of the Aircraft Experimental Station for, as consultant to the Tugan Aircraft Company of Sydney, he was associated with the design of the Codock and its successor, the Gannet, both twin-engined civil aircraft. Over the years, Commonwealth Aircraft has designed and built several new types of aircraft; the C.A. 11 twin-engined bomber with director fire defensive armament; the Boomerang, a major re-design of the Wirraway in which power and performance were increased, and the aircraft became a heavily armed single-seat fighter; the C.A. 12, a fan-cooled turbo-supercharged version of the Boomerang; the C.A. 15, a high performance interceptor fighter in the same class as the Spitfire and Mustang; the Wackett Trainer, a light primary type; the C.A. 23 all-weather transonic fighter, a very advanced and promising aircraft which was not completed, and the Winjeel, an *ab initio* trainer with side-by-side seating. Of these, the Boomerang, the Wackett Trainer and the Winjeel were all built in numbers of 200 or more for the Air Force, a ratio of 3 successful designs in 7 prototypes. This compares favourably with the usual ratio of about one in 8 or 10. The C.A. 15 was also a successful aeroplane but it appeared just as jet aircraft became practical and was immediately out-dated.

On the production side, the Corporation built the Wirraway and the Boomerang. These were followed by the Mustang, Wackett Trainer, Winjeel and Sabre. In the engine factory, the Pratt and Whitney Wasp was followed by the twin Wasp (used in Boomerang and Beaufort), Merlin (Mustang and Lincoln), Nene (Vampire), and Avon (Sabre and Canberra).

The other aircraft factory which first started manufacture in 1936 was the Australian branch of de Havilland Aircraft. It began in a modest way by building Tiger Moths in limited numbers, but during the war the Company expanded greatly. It built or sub-contracted Mosquito bombers, propellers and Gipsy Major engines in large numbers and after the war built Vampires, modified to take the Nene engine. It is now producing Vampire Trainers for the R.A.A.F. The company has made two ventures into the design field. During the war, it designed and built troop-carrying gliders to take a pilot and six men. After the war, it developed the Drover, a small feeder-line aircraft with three Gipsy Major engines. The Company, of course, acts as the Australian outpost of the de Havilland Company in maintaining its aircraft which operate in Australia, from Dragons and Dragon Rapides to Doves, Herons, Beavers, and Venoms.

With the imminence of war, another large aircraft factory was decided upon, this time operated by the Government itself. An Aircraft Production Commission was set up and under it the Government Aircraft Factories were established in 1939. The head was the late Sir John Storey, a dynamic industrialist whose production experience ensured that time schedules and quality standards were fully met in spite of grave difficulties. The Factories, a co-ordinated group, spread over a number of States, built the Beaufort bomber, followed by Beaufighters and then Lincolns. The present production order is for Canberras. The Government Aircraft Factories have only recently entered the design field with the Jindivik, a high performance pilotless target aircraft, designed by Mr. I. B. Fleming, for use on the Woomera Rocket Range. Clearly, this beginning may well lead to further developments in the field of controlled, unmanned aerial vehicles.

The only other current design efforts are private ventures by small firms. The most ambitious is a five-place tandem rotor helicopter designed by G. C. Molyneux, a consulting engineer of Melbourne. A two-seater prototype is being built after extensive wind tunnel testing. The second venture is the P.L.7 "Tanker", an agricultural aeroplane built by Kingsford Smith Aviation Service Ltd. of Sydney. It was specifically designed for top dressing and spraying operations and has some unusual features.

The aeroplane is a single-engined biplane with tail booms and a tricycle undercarriage. The focal point of the structure is a mild steel hopper which carries the

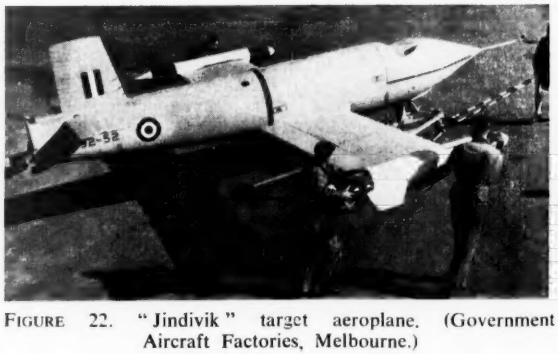


FIGURE 22. "Jindivik" target aeroplane. (Government Aircraft Factories, Melbourne.)

FIGURE 23. Structural details of P.L.7 " tanker " agricultural aeroplane. (Kingsford-Smith Aviation Service, Sydney.)

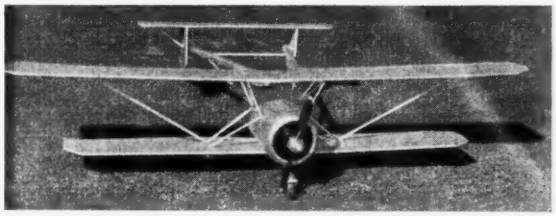


FIGURE 24. P.L.7 " tanker " completed.

engine mount in front and the pilot's cockpit at the rear. The hopper is also stressed to carry the wing and tail loads. Fig. 23 shows the unusual structural arrangement, but the completed aeroplane, seen in Fig. 24 has quite a neat appearance. The hopper is of 45 cubic feet capacity and a hopper load of 2,010 lb. can be carried with full fuel. It can be filled rapidly through an 18-inch diameter hole in the top. A Cheetah X engine gives a very satisfactory performance at the maximum weight of 5,000 lb.

The third venture is a four-place cabin high-wing monoplane with a tricycle undercarriage and Gipsy Major engine, built by Fawcett Aviation Services, also of Sydney.

Unfortunately, this sound foundation of the art of aeroplane design appears to be doomed to crumble away. Aeroplanes of all but the simplest types, such as trainers and light aeroplanes, are becoming so complex and costly that only large and wealthy countries can afford to undertake new designs. Australia cannot compete in the military and larger civil categories and her very limited home market makes even the smaller types of aircraft a chancy commercial gamble.

These factors tend to limit the industry to the production of proven overseas military types; civil aircraft are needed in such small numbers that the cost of locally produced units would be prohibitive. One must, therefore, examine the needs of the Royal Australian Air Force.

The R.A.A.F. needs five types of aircraft: fighter, bomber, transport, coastal reconnaissance and trainer. At present the types in use are Avon-Sabre, Canberra, DC-3 or Bristol Freighter, Neptune and Vampire. The light bomber is not very suitable for implementing a policy of fighting a war away from Australian territory, and it is likely that something heavier and with a long range, verging on the strategic bomber, will take its place.

The question arises as to whether aircraft should be built in the country or imported. To this there is no simple answer; in fact, the issues are so complex and conflicting that the decision becomes a matter of policy. The economics are largely bound up with the numbers required. If orders are limited to 100 or less, two factors increase the cost per unit quite significantly. The first is tooling, which is generally a major initial expense. The difference between an order of 50 and an order of 500 could mean the difference between tooling costs of 30 per cent and 5 per cent of the production cost per unit. The second factor is the so-called " 80 per cent learning curve "[4], which has been proved in practice. This results in the following variation in unit and average cost (basic cost 100).

| *No. Ordered* | 1 | 10 | 100 | 500 | 1000 |
|---|---|---|---|---|---|
| *Unit Cost* | 100 | 33 | 15 | 9 | 6 |
| *Average Cost* | 100 | 48 | 23 | 13 | 11 |

It is clear that other things being equal, a country which builds 100 aeroplanes will do so at twice the cost at which she can purchase them from a country which has the same aeroplane in large production. In spite of this fact, it has been estimated[3] that Australia can compete with the U.S.A. because of wage differentials, but not with the U.K. where labour costs are lower.

Several factors must be weighed against the higher cost of local production. First is the technical support which the constructing company can give the Air Force. In peacetime, it is impossible for a small Air Force to hold an adequate complement of technical personnel to cope with the operational problems of complex modern aircraft. The Service must lean heavily on the manufacturers and it is not very satisfactory if they are many thousands of miles away. Again, the Air Force must strive to keep its aircraft at the zenith of performance and this can only be done by incorporating the latest modifications as soon as possible. This is much easier with a local production, which also makes possible modifications to suit local conditions. Finally, repairs and spare parts are more readily available from the local manufacturer and, in time of war, this has proved a significant advantage.

In spite of these advantages, the Australian aircraft industry is likely to change over to an increasing extent to maintenance and the manufacture of spare parts. Even now, quite large concerns are growing up in this field. In the Sydney area, Fairey Aviation Company has established a factory to maintain Gannets, Fireflys and other naval aircraft, and the Bristol Aeroplane Company has established engine and airframe overhaul facilities with particular emphasis on helicopters. Rolls-Royce has recently completed an engine overhaul factory for Darts and Avons, both widely used in Australia. In the guided missile field, several U.K. manufacturers have established subsidiary companies in South Australia.

I, myself, deplore the trend of events as I feel that it is not in the best interests of the British Commonwealth as a whole, nor even of the western democracies, to have the only major outpost and rallying point in

the Pacific area almost completely dependent for the supply of aircraft on distant nations, who may be heavily involved themselves. Australia has production resources with trained and talented technical manpower, and it appears that these resources may disappear for want of nourishment. It may be argued that guided missiles will ultimately displace aircraft. In the U.K. it is the aircraft firms which are undertaking the manufacture of these weapons as they have suitable equipment and staff. The small size and large numbers required would suit the Australian industry admirably and, whereas aircraft can be flown in from other countries, guided missiles must be transported and local manufacture has considerable advantages. Thus, it is important that the Australian aircraft industry be preserved in the difficult interim period.

## Flight Research and Development in the R.A.A.F.

Since the beginning of military aviation in Australia, in 1913, practical flight testing of one kind or another has been done by the Air Force. Before the last war however, such work was done on an *ad hoc* basis and no organised facilities for it existed.

The necessity for a more scientific approach to the problems of aircraft performance and operation came to be recognised early in the war when locally produced aircraft were coming into service and aircraft of a variety of types not previously seen in Australia were being received from overseas. Early in 1941, a small flight was established by the R.A.A.F. for this work, the mathematical analysis of performance problems being undertaken by scientific officers of the Aeronautical Research Laboratories.

At the end of 1943, a larger unit, then known as No. 1 Aircraft Performance Unit, was established, in which provision was made for specialist sections to deal adequately with such matters as armament, radio, instrumentation, photographic work, and so on. The Unit continued to expand until the end of the war and its work during this period was naturally confined to military problems. By this time, the contribution of staff from the Aeronautical Research Laboratories had ceased, since suitably qualified officers were available from within the Service, but a close co-operation in flight research was maintained between the Unit and the Aeronautical Research Laboratories. Moreover, other Government establishments and industry began to make such demands upon the Unit that the establishment was increased and it became known as the Aircraft Research and Development Unit (A.R.D.U.).

While A.R.D.U. is generally similar to the Aeroplane and Armament Experimental Establishment, in that performance and armament work are probably its main actitivies, it also has, naturally on a very small scale, some of the functions of other U.K. establishments, such as the Royal Aircraft Establishment, Telecommunications Research Establishment, and the Radar Research Establishment. That is to say, it covers investigations into such matters as aerodynamic problems, defects and special modifications, and the development and testing of radio ground and air installations and navigational equipment.

Australia is relatively close to the tropical regions of the Far East, and tropical trials on aircraft has always been an important activity of A.R.D.U. It is possible to go in one day from the temperate climate of Melbourne to the tropical climate of Darwin and extensive use has been made of the latter locality for such trials. The tropopause is higher in the tropics than in temperate latitudes and the air is considerably colder, temperatures of $-90^{\circ}C$ being quite common in the stratosphere; this fact is of importance in the testing of turbine engines, the characteristics of which may be greatly modified by low temperatures. At the same time, the high ground temperature and high humidity aggravate the problems of air conditioning aircraft.

Although the greater part of the work of the Unit is directly concerned with Air Force requirements, special assignments are undertaken. Two which involved long ranges and careful flight planning techniques were the survey of Macquarie Island in the Antarctic and the England-New Zealand Air Race in 1953. Work is also done for non-military Government Departments and the aircraft industry. An example was the successful development, in association with the Victorian Department of Agriculture, of techniques for aerial spraying to combat the plague locust, which has periodically devastated regions of Southern New South Wales and Northern Victoria. Mention may also be made of such trials as the assessment of the safe loading and handling characteristics of various civil aircraft and an extensive investigation into the characteristics of the helicopter, with particular reference to its utility in forestry and bush fire fighting. Among purely research projects may be mentioned the joint investigations by A.R.D.U. and the Aeronautical Research Laboratories in the field of boundary layer control. Flight development of the suction wing glider fitted with the Glas II aerofoil was followed by research on boundary layer control by means of air jets, using a Vampire, and at present the Avro 707A delta aircraft is being used to explore boundary layer flow on highly swept wings.

In 1948 a major civilian research activity developed with the formation of a detachment to work with the Division of Radio Physics of the Commonwealth Scientific and Industrial Research Organisation. One of the first tasks was the flight testing of the Distance Measuring Equipment now in use on the civil air routes of Australia. Work on other radio aids has continued, but the most important work of the detachment is now the provision of flying facilities for investigations into meteorological phenomena associated with the formation of rain. Considerable success has been achieved by the Division of Radio Physics in the study of cloud physics and definite progress made towards the possibility of inducing rainfall by artificial means. More recently, another detachment of the Unit has been formed to work in association with the Electronics Division of the Weapons Research Establishment in the development of purely military navigational aids.

When the Rocket Range was first established in Australia, a detachment of A.R.D.U. was set up to conduct all experimental flying associated with weapons trials; for example, bomb ballistics trials. The development of techniques for the flying of unmanned aircraft has been an important contribution of A.R.D.U. towards the work of the Range. With the ever-increasing volume of such activities however, it has recently become necessary to form separate units which are solely concerned with weapons research flying activities. Nevertheless, existence of a unit such as the A.R.D.U. was of great value in getting the flying activities of the Range under way in the early stages.

## Guided Missiles

Returning once again to Sir Ben Lockspeiser, the desert which the U.K. wanted for dangerous aeronautical experiments has become a reality in Central Australia. The headquarters of the range is at Woomera in South Australia, from which it stretches to the north-western seaboard, 1,250 miles away. A supporting base establishment is located at Salisbury, some 16 miles north of Adelaide, the capital of South Australia. These two establishments are known jointly as the Weapons Research Establishment of the Australian Department of Supply and, although administered and almost wholly staffed by Australia, finance and technical control are the joint responsibility of both the U.K. and Australia.

The project began officially in March 1947, by which date a group of U.K. scientists, under Lieutenant-General Evetts had selected Woomera as the outdoor testing range for guided weapons. The terrain is mainly an open plain of typical low grade sheep country. The rainfall is extremely low, averaging less than 7 in. per year. The country is useless for anything but sheep growing and the greater part of the area selected was, in fact, uninhabited. With a few safety precautions, little interference to the work of the pastoralists has been necessary. The atmosphere is exceptionally clear and extremely suitable for photographic observations; for example, weather balloons

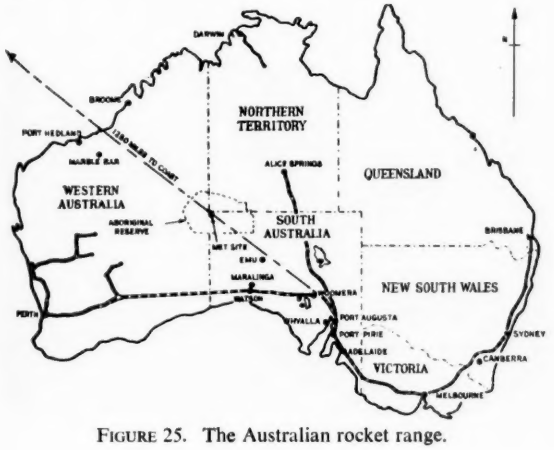



FIGURE 25. The Australian rocket range.

FIGURE 26. "Mud Jeep" fitted with low pressure tyres for reconnaissance of rocket range.

can be followed up to 100,000 ft. The absence of rainfall raised one major problem, the water supply. This was solved by constructing a pipeline 110 miles long from Port Augusta to provide 220 million gallons of water per annum to Woomera.

The selection of the site of Woomera and the immediate technical areas was merely the beginning of a long series of reconnaissance surveys which had to be undertaken. The country is extremely difficult of access in some parts. The absence of water is the predominant feature and travel by conventional vehicles is almost impossible. Extensive experiments were made with special vehicles capable of travelling through the extremely loose sandhills, or through the boggy conditions which follow on the falling of the infrequent rain and which can be very treacherous indeed.

The scale of the range is impressive. There is a technical area, a high altitude bombing range, the head of the long range itself, two airfields and a township of 3,000 for the staff, their families and the amenities they require for ordinary living. The range head, for example, has launchers, complex instrumentation centred in a large building, blockhouses, camera posts, and a number of assembly buildings for contractors. Because of the climate and the dust, many of these are air-conditioned. As a measure of size, the range head, or firing centre, is 30 miles from Woomera township—almost the distance between the R.A.E. and Ministry of Supply Headquarters. Good roads connect the various facilities and travel is quick, the only hazard in speeding being the stray kangaroo or emu. This separation, for safety of course, of the main technical centre from the range was the motive for building two aerodromes. Missiles for test can be flown direct to the range, although Evettsfield, the range airfield, is mainly used for taking off and landing pilotless target aircraft. These could well be a hazard on the main airfield from which the passenger transport service and R.A.A.F. aeroplanes are operated.

Woomera township has some 500 family dwellings of good suburban standard, messes and quarters for transient and Service personnel, churches, a modern

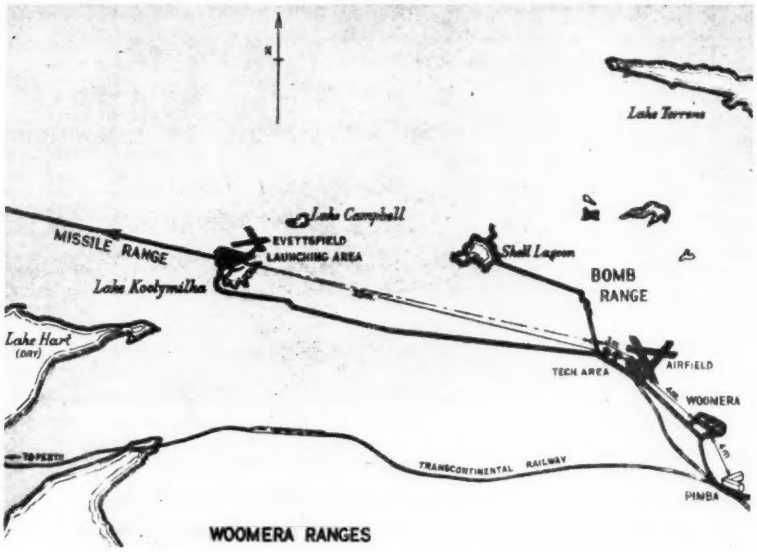



FIGURE 27. Woomera—technical area, ranges and airfields.

school, shops, cinema, and even a jail. A rather special feature is the Arboricultural Section which was established to study the best means of growing trees, shrubs and grasses for the dual purpose of improving the appearance of some of the areas and to keep down the ill effects of dust and soil erosion. A nursery was established and literally the entire world was combed in an endeavour to find the best types of plant to grow in the Woomera area. A tremendous amount of knowledge was accumulated and the subsequent transplanting of suitable species to Woomera has been carried out on a very large scale. The full beneficial effects of this programme will be realised in a few years time.

During missile tests, the information is necessarily received at a high rate during a relatively short interval of time. Ciné film is used extensively for photographic records, but endeavours are being made to improve on it and high speed magnetic tape is now also used to record information from observation points, or from the missile itself. To synchronise and correlate the various control and recording devices, a central timing unit links all the salient operations together by an extensive network of telephone circuits and radio links.

Guided weapon trials involve an immense amount of computational work. As the programme of succeeding trials often depends on the results of previous ones, the time taken to obtain results should be as short as possible. The mathematical work is done in a variety of ways; firstly, there are teams of girl computers who study photographic films and other records patiently, utilising all the aids which science now makes possible. Punch card calculating machines of the Hollerith type lessen the burden of tedious mathematical work, but the ultimate aim is to use electronic digital computers which can be operated directly by the magnetic tape on which the trial results have been recorded. Such a digital computer is now in operation. In the case of telemetry records, the analysis time has already been reduced from 120 girl-hours to 35 minutes. A large analogue computer has also been installed. Known as AGWAC, it is used mainly for planning trials and analysing performance.

Woomera is unsuitable for scientific and manufacturing work as it is 240 miles from a University or large scale engineering industry. Hence, a base establishment at Salisbury was necessary. This covers an area of six square miles and has a first rate aerodrome named "Edinburgh Field" by the Duke of Edinburgh, which forms the headquarters of the R.A.A.F. Air Unit attached to the Range. It is also the terminal for the U.K.-Australia Hastings air service. The Establishment itself contains extensive laboratories for electronics, optics, trials assessment, range instrumentation and high speed data reduction. The functions of the Establishment are to provide all engineering and instrumentation facilities for the range; to assess new weapon systems in order to devise the test programme and any new instrumentation required; to process the data in a very short space of time and to conduct basic research in fields allied to guided weapons. The fields chosen are electronic guidance, propulsion systems and aerodynamic characteristics, and separate research divisions have been established to specialise in these important matters.

The Electronics Research Division covers a wide range of techniques for tracking, guidance and high speed recording.

The Propulsion Division studies the chemistry of fuels and suitable oxidants and the metallurgical and other problems involved in the development of rocket motors and similar devices to make the most effective use of these fuels.

FIGURE 28. Instrumentation building at Woomera range head.

The Aerodynamics Division is concerned with aerodynamic and related aspects of guided weapons. It has been provided with a modern supersonic wind tunnel in which research can be carried out or tests made on models of partial or completed guided weapons or similar devices. This wind tunnel, with a working section 15 in. × 15 in., will provide facilities for testing up to a Mach number of 2·8. The Division also does field work at Woomera in aerodynamic and aeroelastic problems by making use of ground-launched rocket test vehicles to carry through the air wings, bodies, or tails of various kinds which are the subject of investigation.

Also located in the area are a number of firms. These are nearly all Australian branches of U.K. firms connected with guided weapon projects which are being, or will be tested on the range.

While the rocket has become a trademark for Woomera and Salisbury, the climatic and other conditions are so favourable that many other trials of a scientific character can be carried out there under better conditions than are obtainable elsewhere. The result is a tendency for Woomera and Salisbury to become an important centre for a much wider range of scientific research and testing work than is implied in the term "guided weapons".

Guided weapon testing and associated research is a joint activity between the U.K. and Australia, and the immense distance of 12,000 miles which separates them is a formidable barrier to the working of the scheme. This has been overcome by instituting a regular courier service of Hastings aircraft which, on an average, fly once a week in each direction. These aircraft can carry the actual missiles to be tested, special stores and the personnel connected with the projects. It is probably true to say that the range could not function without this artery. It has also been possible to use the service for the transport of scientists working within the framework of the C.A.A.R.C. Co-ordination Scheme.

It is realised that the description of the Weapons Research Establishments at Woomera and Salisbury is inadequate, but Security considerations prevent any more detailed account of the work. The main purpose of including guided weapons was to show a splendid example of a joint aeronautical activity by two countries of the British Commonwealth. It makes clear that if the will to use the special facilities of each country is there, the enormous difficulties of distance and communication can be overcome to the great benefit of the British Commonwealth as a whole.

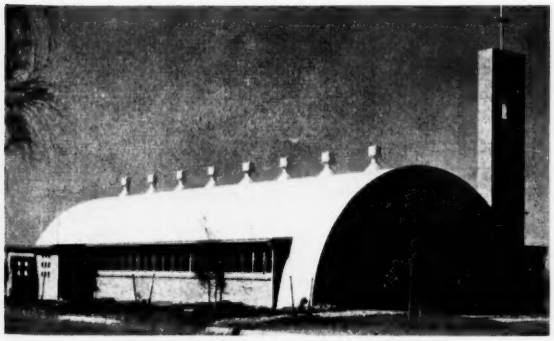


FIGURE 29. One of the Churches at Woomera.

FIGURE 30. Weapons Research Establishment, Salisbury, South Australia.

## Aeronautical Research

Chronologically, and even if we except the prehistoric experimenter who produced the boomerang, research was the first aeronautical activity in Australia. Lawrence Hargrave was the pioneer worker in this field and the author of 19 papers which appeared in the Journals of the Royal Society of New South Wales between the years 1884 and 1909. He was an experimental research worker of the highest calibre and made many contributions of a fundamental nature. Unfortunately, because of the poor dissemination of aeronautical literature at the time, much of Hargrave's work consisted of re-discoveries. He established by his own experiments the superiority of the cambered aerofoil over the flat plate, and the stabilising effect of a reflexed trailing edge. He also appears to have pioneered the rotary aero engine and the box-kite. This remarkable man is commemorated in the name of the Chair of Aeronautics at Sydney University, which was established in 1940. In May 1956, the Melbourne Branch of the Society inaugurated an annual lecture in his honour.

There was a great deal of discontinuous effort, mostly of an *ad hoc* kind until 1937 when Mr. H. E.

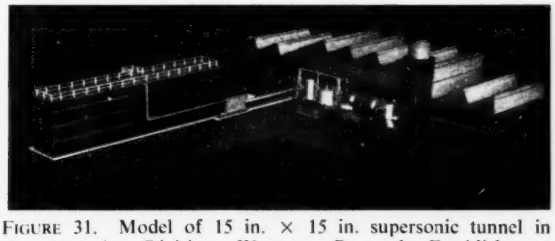


FIGURE 31. Model of 15 in. × 15 in. supersonic tunnel in Aerodynamics Division, Weapons Research Establishment. Large cooler can be seen in foreground.

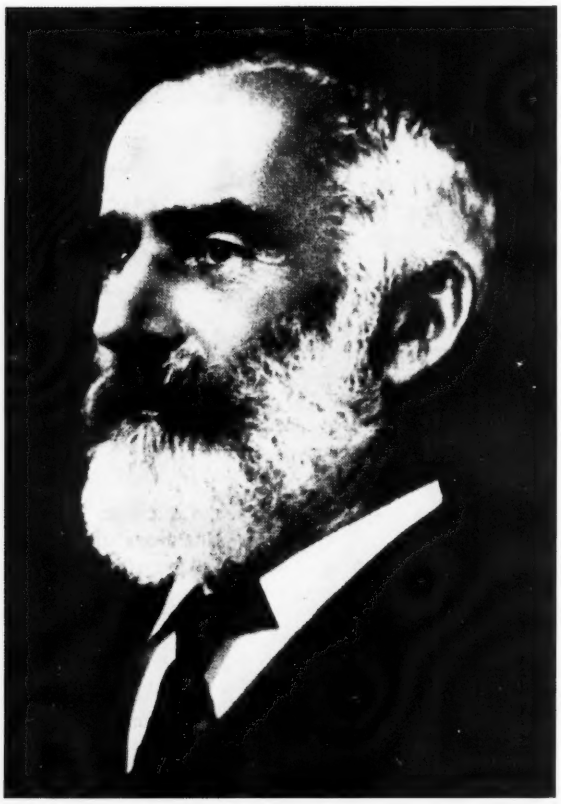


FIGURE 32. Lawrence Hargrave.

Wimperis, a Past President of the Society, recommended to the Commonwealth Government that an Aeronautical Research Laboratory on a substantial scale be established in Melbourne to meet the needs of the aircraft industry. As we have seen, it had been decided during the previous year to initiate the large-scale production of aircraft and engines. The first buildings were completed at the beginning of 1940, and the first wind tunnel began operation two days before Pearl Harbour. This was typical of the early phases of this laboratory. It was a period of rapid growth, but the effort was all directed to some immediate wartime need. Thus, many types of Japanese engines were assembled from crashed units and evaluation tests made; the practicability of using Australian timbers to replace scarce aluminium alloys was proved; excessive engine wear due to dusty training and operational aerodromes was tackled; and most important, considerable help was given to the aircraft design teams in the evolution of new or modified aircraft. This recital could be extended, but we need to note only the salient facts: the Laboratory was completed in time to play a worthwhile part in the Australian war effort but, as might be expected, the work was almost completely of an *ad hoc* type.

Nevertheless, good equipment for aerodynamic, structural, metallurgical and power plant investigations was assembled, together with a number of keen young scientists. These were valuable assets when the war ended, but enhancing these tangible items were the ideas for research which the staff had conceived as the result of the *ad hoc* war work. There was one major difficulty; were these ideas really as good as their originators believed or were they already current and being worked on elsewhere? This pointed to co-ordination with at least the U.K. Fortunately, the U.K. also had the same objective, but for another reason, namely, the best utilisation of all British Commonwealth resources to meet the challenge of countries with large resources for aeronautical research and development.

A Commonwealth Aeronautical Research Conference was convened in London in 1946 and from this stemmed the Commonwealth Advisory Aeronautical Research Council. This body invited membership from all the British countries, but so far only the U.K., Canada, Australia, New Zealand, South Africa and India have participated. Meetings of the Council have been held in Australia in 1948, Canada 1950, U.K. 1953, and again in Australia during 1955. Co-ordination is actively continued between these meetings by nominated specialists in various fields of aeronautical research, who correspond with and meet their opposite numbers in other countries. The Council at its Meetings makes recommendations for the most worthwhile directions in which to channel effort and, as far as Australia is concerned, these recommendations have not only been of great assistance in formulating programmes, but have been the means of obtaining the requisite equipment and staff to undertake researches on quite a large scale.

In between the main meetings, an endeavour is made to hold meetings of co-ordinators in the six or seven fields of research so that reports on these activities can be presented to the Council. As may well be imagined, it is not easy to persuade Governments to send numbers of scientists up to 12,000 miles in each

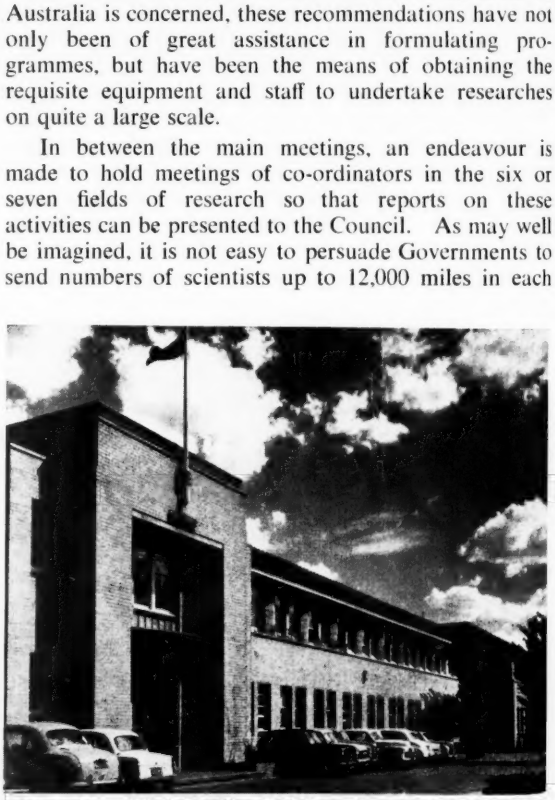


FIGURE 33. Administrative Building, Aeronautical Research Laboratories, Melbourne.

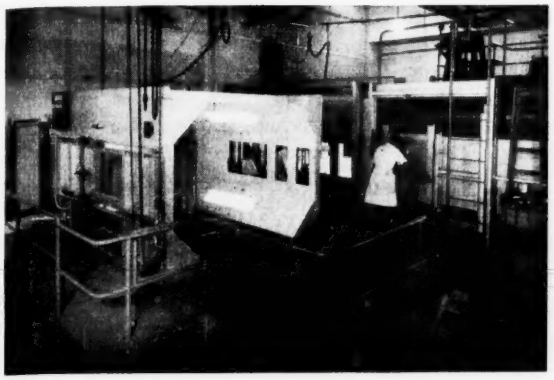


FIGURE 34. 9 ft. × 7 ft. wind tunnel at Aeronautical Research Laboratories with interchangeable working sections (a second experiment has been set up in the inactive working section).

direction to attend meetings. Here, the Courier Service of the Woomera Rocket Range has been able to accommodate these extra people and this has made the scheme workable. Early in 1955, the Canadians also helped with R.C.A.F. transport across the Atlantic, so that a number of Australian scientists were able to travel to Canada for Co-ordination Meetings entirely by these special forms of Government transport.

The term research is a very elastic one and I should like to use the simile of a spectrum with fundamental or academic research at one end and development at the other. We at the Aeronautical Research Laboratories are well aware of the value of unfettered basic research, but we have always tried to have a broad practical end in sight, however distant that may be. During the war, the objectives were immediate and urgent. After it, there came a period during which fundamental studies predominated. In the past few years, the Laboratory has become one of the defence group, and development projects have been undertaken at the same time. The growing preponderance of operation as compared with manufacture of aircraft in Australia has biased research towards operational rather than to design problems. This has not meant any weakening of our basic research effort, but new studies such as human factors in design and operation have been started.

It would not be appropriate to attempt any comprehensive account of Australian researches. Indeed, annual reports are issued with full references. Instead, I propose to confine the account to four or five of the main projects which are current and representative of the different fields in which we work.

## Fatigue and Life of Aircraft Structures

Until the end of the Second World War fatigue was regarded mainly as a nuisance which affected the secondary structure of aeroplanes. The danger of fatigue failure in the primary structure of the aircraft due to fluctuating loads in flight was completely disregarded. In January 1945, a Stinson airliner VH-UYY broke up in the air in Australia and crashed

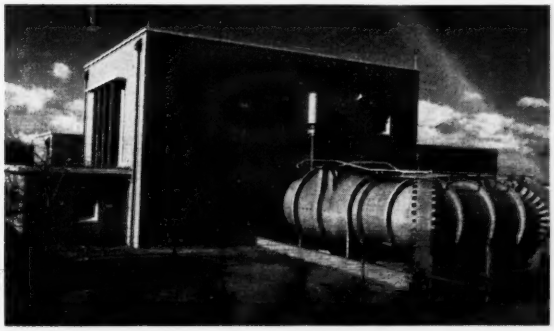


FIGURE 35. Variable pressure transonic wind tunnel at Aeronautical Research Laboratories, Melbourne.

with the loss of ten lives. Examination of the wreckage[6] proved conclusively that the failure was due to fatigue at a region of stress concentration in the tubular steel tension member of the main spar. The structure was non-redundant, and the formation of the crack led inevitably to failure. Thus, Australia was awakened to the possibility of fatigue failure and the need for devising methods of assessing a safe endurance life for aircraft structures.

Members of the Department of Civil Aviation and the Aeronautical Research Laboratories agreed that a programme of work on this topic would be undertaken. Mr. H. A. Wills, who was then in charge of research in structures and materials, planned a comprehensive attack on the problem; measurements would be made of the loads and stresses produced in aircraft by normal operations, atmospheric turbulence, and so on, while at the same time the fatigue characteristics of structures and materials would be determined by laboratory tests on full-scale structures, as well as on small specimens of material and on component parts.

The Laboratories already had the apparatus for static testing of aircraft wings and within a few months modifications were made to permit rapid automatic loading and unloading of the wings under test. Moreover, the end of the war made it possible to obtain large numbers of surplus aircraft wings or other parts for the full-scale laboratory tests.

At the same time, the collection of flight load data was begun with the co-operation of the R.A.A.F., the Department of Civil Aviation and civil aircraft operators. *V-g* recorders were installed on aircraft on all the major air routes in Australia and also to Japan. These results showed that the severity of the loads depends critically on the route followed, and also on the season; they give little hope of establishing a single average gust spectrum which is applicable to all aircraft types travelling on all routes. In 1951, R.A.E. counting accelerometers and fatigue meters became available and these have superseded the *V-g* recorders which provided data of a restricted character. We are now obtaining information on routes from Australia to Japan, America and South Africa, as well as on a number of internal routes. Australian airlines have

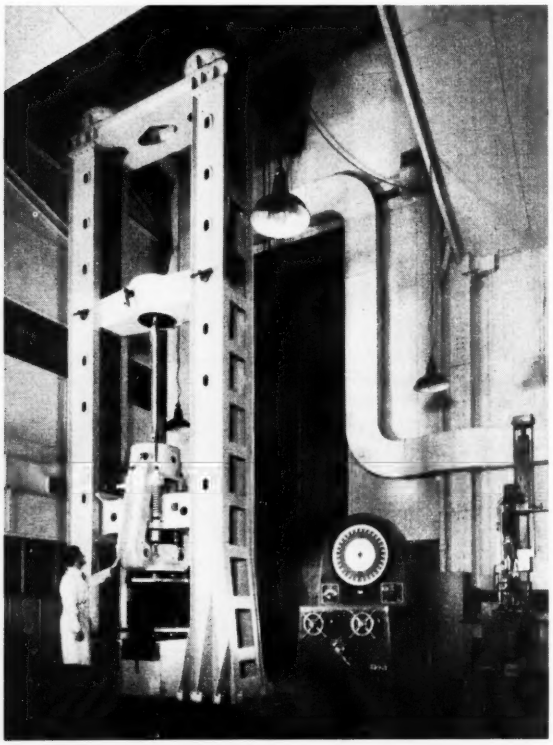
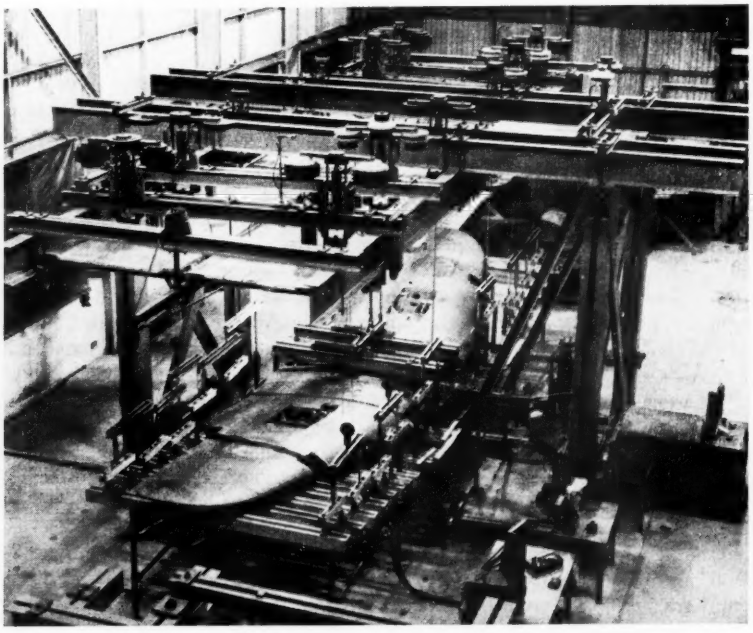


FIGURE 36. 600,000 lb. universal testing machine at Aeronautical Research Laboratories.

FIGURE 37 (*below*). Hydraulic loading rig for repeated load tests on wings.



co-operated enthusiastically while D.C.A. has made the installation of fatigue meters mandatory in all new big transport types to provide data for each aircraft.

*V-g* recorders have also been installed in aircraft of the R.A.A.F. to measure manoeuvring loads. In training aircraft the somewhat unexpected result was found that there is a distinct possibility of fatigue, particularly in aircraft practising dive bombing. The number of repetitions of load is not large, but the " pull-out " load during each practice run is extremely high. Another interesting piece of work was done in collaboration with the Ministry of Supply, whereby *V-g* records were obtained from an R.A.A.F. unit on combat duty in Korea.

The essential objective in this work was to obtain the factual data necessary for an assessment of the safe life of an aircraft in service. In September 1947, Mr. Wills presented a paper[7] to the Institution of Engineers, Australia, in which he reviewed the current situation. He pointed out the design trends which were increasing the likelihood of fatigue failure, delineated the fields in which further research work was urgently required, and put forward a method of life calculation in which the fatigue damage resulting from fluctuating loads of each amplitude was summed according to the now well-known cumulative damage rule. Later, Mr. Wills was invited to speak about this work at the Second International Aeronautical Conference held in New York in May 1949[7].

The laboratory work has continued energetically since its first inception and the fatigue strength of three different types of aeroplane wing has been investigated. The first was the Mosquito, which was of glued wooden construction. These wings sustained many thousands of repetitions of 90 per cent of the failing load and then failed under approximately the same static load as virgin specimens. The conclusion was that the glued wooden wings were not susceptible to fatigue failure. The matter was not pursued very far because wooden aircraft are obsolete, but the most likely explanation is that glued construction does not induce stress raisers, whereas, of course, riveted metal members have hundreds of these.

There followed a series of tests on 14 metal wings from Boomerang fighter aircraft, the wings being of the single spar type. The wings were tested at a number of values of fluctuating load amplitude and an *S-N* curve established. In order to define the tail end of the curve, where small loads were repeated many millions of times, a rig to vibrate the wing at its resonant

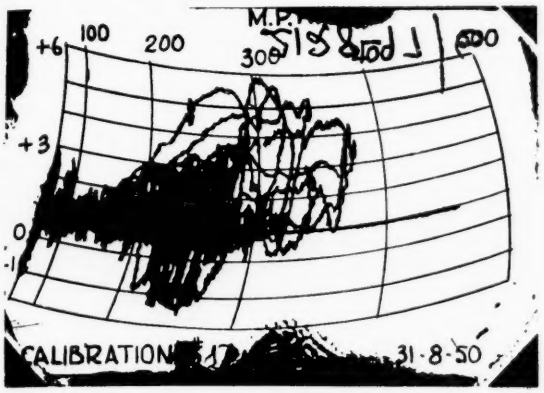



FIGURE 38. *V-g* record from Mustang aircraft used in training. The aircraft was engaged in air-to-ground gunnery and dive bombing.

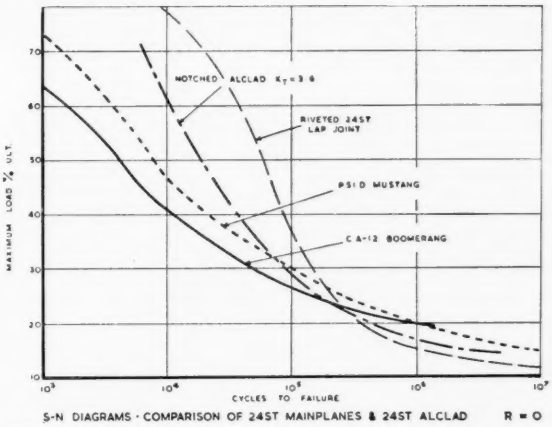

NOTCHED ALCLAD $K_T = 3.6$
RIVETED 24ST LAP JOINT
P51D MUSTANG
CA-12 BOOMERANG
MAXIMUM LOAD % ULT
CYCLES TO FAILURE
S-N DIAGRAMS · COMPARISON OF 24ST MAINPLANES & 24ST ALCLAD R = 0

FIGURE 40. *S-N* curves for wings and typical joints made of 24S alloy.

frequency was devised. When compared with available data for riveted joints at low alternating stresses a reasonable agreement was obtained but, at stresses approximating to 40 per cent of the ultimate, the wing life was only 1/20th of that of the riveted joints.

In 1950, a test programme on Mustang wings was begun and is now complete. This sets out to determine the endurance under cyclic loading over the whole relevant range of alternating and mean loads, and to see how rates of crack propagation and types of failure varied with the load range. By this time, the importance of "scatter" in fatigue test results was realised so that it became necessary to test a number of wings at each value of alternating and mean load; in all, about 100 wings were tested.[9] Repeated load testing on such a large scale has, we believe, not been done elsewhere.

In parallel with work on complete wing structures, specimens of material and forms of construction have been tested in the various types of testing machines. In the 1940's it was found that tests on the same material in different laboratories yielded results which could not be correlated or reproduced because specific details of the manner of testing and methods of preparation were not given. It was clear that the endurance was very sensitive to the condition of the surface and of the sub-surface layer, and an investigation was undertaken in our Laboratories to determine the effect of various surface finishes on the fatigue strength of aluminium alloy (24 ST) material. Other important investigations were made of strength reduction factors resulting from notches[10], and of the effects of testing at various rates of stress reversal[11]. At the same time, more fundamental studies were made of the mechanism of fatigue failure and of the development of slip bands and other metallurgical features during fatigue stressing.

The importance of this work was tragically highlighted in January 1952, when a Dove aircraft failed in flight in Western Australia with a total loss of life, and it was discovered that another Dove which had flown a similar number of hours had major cracks in the same critical member. It is believed that aircraft in America have also failed in fatigue, although not much publicity has been given to the accidents.

The fact that the Dove accident occurred in Australia was due not to the severity of service loads, but to the very high utilisation of aircraft in this country; the two Doves referred to had exceeded 9,000 hours before similar aircraft elsewhere had reached 5,000 hours. It might not be too strong a statement to say that the world, in general, became rapidly fatigue conscious after this event, although Australia had been preaching this particular gospel for some years.

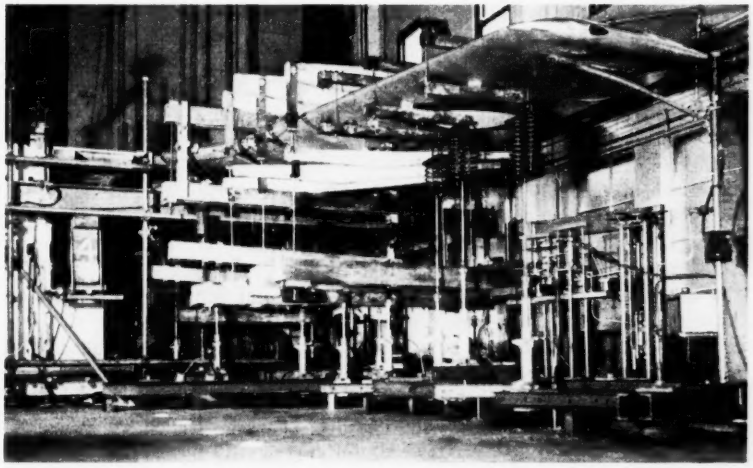


FIGURE 39. Resonant rig for fatigue tests of wings.

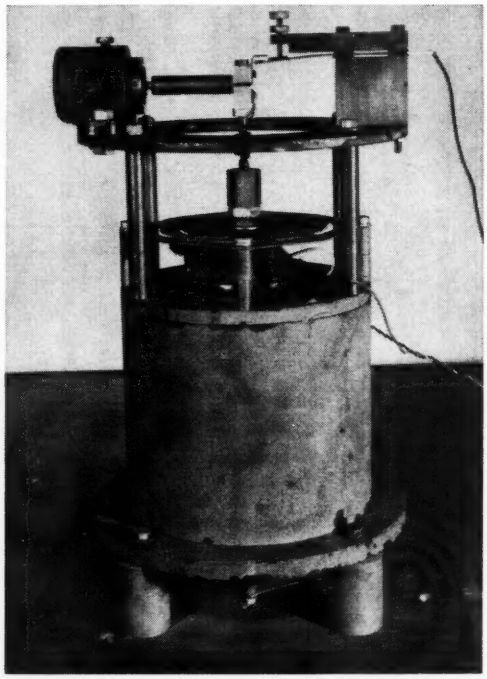


FIGURE 41. Random noise fatigue machine.

Since the tragic Dove crash the Department of Civil Aviation has made a continuous study of the fatigue characteristics of all Australian civil aircraft used by the airlines, whether their origin be American or British. In every case where there is any reason to fear an early failure, a detailed calculation of the life has been made and safe lives laid down. Already seven separate aircraft types have been affected by modifications or replacements of components as a result of these studies.

The Department has used the basic methods of estimation and detailed research data obtained at A.R.L.[12], and gust data obtained in the airlines. It has combined these with a number of detailed refinements developed by its own engineers to keep the results in close accord with the practical experience so dearly bought. By always correlating the latest methods of estimation of life with the application of the same method to the case of the "Dove," the Department has been able to avoid the wide fluctuations of estimated safe life which have occurred elsewhere and a steady and safe middle course has been steered down the years.

Any estimate of life of a structure subjected to irregular load sequences, as in atmospheric turbulence, requires either a test under the actual conditions or some theory for the summation of the fatigue damage due to various parts of the load history. Commonly the cumulative damage rule due to Palmgren and Miner is adopted, although it is known to be inaccurate, while with a completely irregular sequence the whole method of interpretation of the rule is ill-defined. Work to elucidate the effect of irregular loading is proceeding at Aeronautical Research Laboratories in two parallel series of experiments. The first is on material specimens, where the irregular load sequence originates in the random noise from a thermionic valve; this is amplified and force applied to the specimen by a "loud speaker" type of vibrator unit. The wave form of the oscillation applied to the specimen can be controlled to produce a load spectrum similar to that encountered in atmospheric turbulence. The rate of loading is high and specimens can be tested to millions of cycles in a few days.

The second approach is by testing full-scale wings using a random loading device. Operating through the normal system of hydraulic jacks this device selects in a random sequence a series of eleven upward and eleven downward loads. The numbers and magnitudes of the loads follow a similar pattern to a typical gust spectrum. Unfortunately, this type of test is rather slow and it will be some time yet before sufficient results are available to substantiate the current cumulative damage rule or to suggest a new one. It should be stated that this random load investigation is a good example of Commonwealth co-ordination in aeronautical research. The R.A.E. was also aware of the importance of establishing the effect of random loading and had given thought to the possibility of undertaking some tests. A meeting of Co-ordinators in the field of Structures was held under the auspices of C.A.A.R.C. in Australia in March 1955, and it was there agreed that Australia, being farther forward in the devising and engineering of the test facilities, should undertake this aspect of the work, leaving the R.A.E. free to concentrate on other things.

## Control of the Boundary Layer

The second research I should like to describe had its beginning in the 1946 Commonwealth Aeronautical Conference. Besides asking for a desert and a waterfall, Sir Ben Lockspeiser suggested to Australia that it should undertake the flight development of the thick suction wing.

This particular form of wing in which the flow was stabilised by suction, had been invented by Dr. A. A. Griffiths in the U.K. and extensive wind tunnel tests on two-dimensional wings had been made during the war. While these were extremely promising, no full-scale application in three dimensions had been made. The idea was received enthusiastically by Australia, and although the limited resources for designing and constructing a full-scale aeroplane were a great difficulty, this was overcome by making the initial flight experiment a relatively simple one. A new wing was built for a troop-carrying glider and an engine-driven plant was housed in a fuselage to provide suction. The wing itself was 30 per cent thick, as one of the principal uses seen for this type of section was the all-wing aeroplane, in which passengers would be housed within the thickness of the wing. This was possible in quite a small aeroplane with a thickness-chord ratio of this magnitude.

A great deal of wind tunnel development was necessary to adapt the principle to a three-dimensional

wing and, in the process, a considerable amount was learned about control of the boundary layer, design of slots, and related matters. The wing itself was flown successfully and a complete flight investigation made. This was reported to the Anglo-American Conference of 1951[13] by T. S. Keeble who, with R. W. Cumming, was responsible for this project. An unexpected trend in civil aviation halted this particular research. The rising costs of aeroplanes brought utilisation in as a major factor in the cost of operation, and there was thus a premium upon speed. This factor, coupled with the demand for speed by passengers, ruled out thick wings with their compressibility speed limitations. The research was therefore discontinued without going to the next phase of building a complete power-driven flying wing aircraft.

The experience gained in boundary layer control led to the suggestion by C.A.A.R.C. that Australia should continue in this field, but turn attention to thin wings suitable for high speed aircraft. To this end the major undertaking of the boundary layer control group in recent years has been an investigation of the potentialities of a new method of boundary layer control[14]. This consists of discharging air through holes drilled in the aerodynamic surface and will be referred to as the method of "air jets". In this investigation[15] the emphasis has been on improving the stalling characteristics of thin swept wings.

It has been established that air jets can have two beneficial effects as regards the suppression of flow separations: by producing earlier transition in the boundary layer they can minimise the effects of laminar separation, and they can also delay the separation of a turbulent boundary layer.

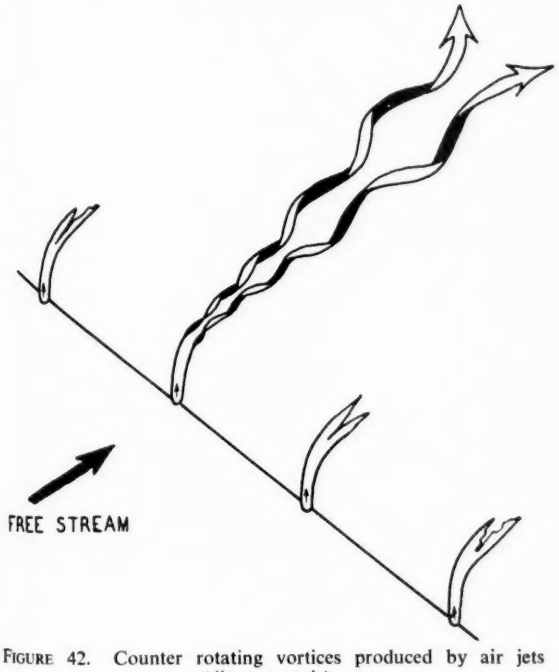



FIGURE 42. Counter rotating vortices produced by air jets (diagrammatic).

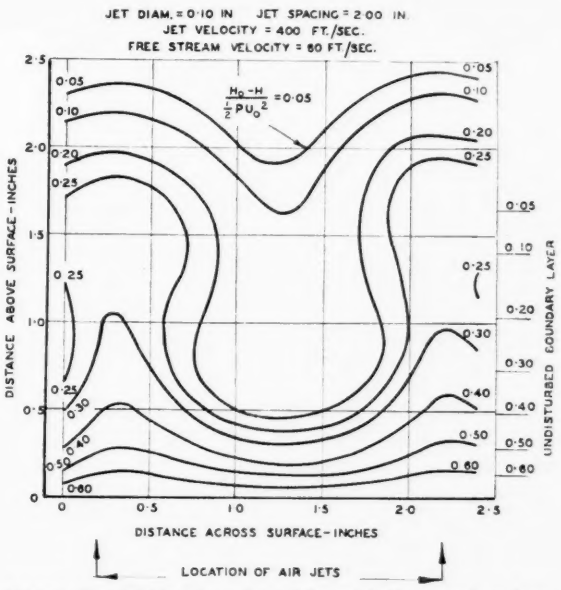

JET DIAM. = 0·10 IN. JET SPACING = 2·00 IN.
JET VELOCITY = 400 FT./SEC.
FREE STREAM VELOCITY = 80 FT./SEC.
$\frac{H_0 - H}{\frac{1}{2}\rho U_0^2} = 0.05$
DISTANCE ABOVE SURFACE-INCHES
DISTANCE ACROSS SURFACE-INCHES
UNDISTURBED BOUNDARY LAYER
LOCATION OF AIR JETS

FIGURE 43. Distribution of total head within boundary layer 12 in. downstream of air jets.

An example of the first effect is that when they are located in a spanwise row on the lower surface and close to the leading edge of a thin wing, they produce earlier transition in the laminar separation bubble and this leads to an increase in the nose stalling incidence of the wing. For this application very small flow quantities are needed.

It has also been found that air jets can delay turbulent separation by a mechanism similar to that of counter rotating vortex generators. A pair of counter rotating vortices is formed by each jet, as shown diagrammatically in Fig. 42. The effect of a typical arrangement on the distribution of total head within the boundary layer is shown in Fig. 43. It is seen that the induced velocities arising from the vortices lead to an appreciable thinning of the boundary layer between the jets, and this explains the effectiveness of the jets in delaying turbulent separation. The hole diameter, hole spacing and jet velocity must be correctly chosen to give the desired vortex configuration, and approximate criteria to do this have been established experimentally.

There have been a number of interesting by-products of this work on air jets. For example, it has been found that at other than fairly small values of Reynolds number, the nose stall of thin wings results from turbulent separation occurring downstream of the small laminar separation bubble and not from a breakdown of the flow in the bubble itself, as had previously been generally accepted.

Other experiments have shown that suitable surface roughness can increase the stalling incidence of a thin wing and this in turn led to an investigation[16] of the downstream effect of a thickening of the laminar boundary layer. It was found that the thickening

decreases rapidly in a favourable pressure gradient but is magnified by an adverse one.

The ramifications of boundary layer control are immense and are particularly important in relation to heavily swept and delta wings. One of our staff who is in the U.K. on secondment to the National Physical Laboratory, is working closely with an aircraft firm on the application of the air jet principle to a well-known aircraft. Broad U.K. interest is shown by the loan to Australia of one of the Avro 707 Delta aircraft, which was arranged at the suggestion of C.A.A.R.C. The flight programme for this aircraft will be almost entirely concerned with the measurement of boundary layer characteristics of the delta wing. Wind tunnel investigations will be conducted in parallel and, if methods of increasing usable lift prove practicable from the model tests, the aircraft will later be modified for full-scale confirmation.

## Research of Chromium Alloys

I should now like to describe two researches in the field of gas turbines. The first is metallurgical in character. The continuing requirement for higher operating temperatures in the aircraft gas turbine has been met, over the past fifteen years or so, by spectacular advances in the high temperature strength of commercially available alloys. Improvements to these alloys continue to be made and, for example, Nimonic 100 has recently been developed and shown considerable improvements over its justly famous predecessors. All established alloys in use, however, are based on one or other of the three related metals, iron, nickel and cobalt, and since the desired operating temperatures have already risen to within a few hundred degrees of their melting points, it is evident that, if operating temperatures are to be pushed substantially higher without forced cooling of the turbine blades, the present alloys will not be satisfactory.

Recognition of this situation has resulted in a considerable volume of laboratory research on higher-melting materials in various parts of the world. At the Aeronautical Research Laboratories a comprehensive review[17] was made some years ago and, on both theoretical and practical grounds, chromium was chosen as a promising basis on which to develop new heat-resistant alloys. Among its more obvious advantages, chromium has a melting point more than 300° higher than that of iron, its density is some 12 per cent less, and it is capable of forming a surface film which is highly resistant to oxidation. Also, both world and Australian resources of chromium ore are good, although the latter are as yet largely undeveloped.

When the A.R.L. project was begun, little was known of chromium-based alloys in general and thus the early work was necessarily concerned with constitutional studies of the alloys of chromium with such solute metals as beryllium[18], titanium[19], tungsten[20], and zirconium[21]. The refractory nature of these alloys meant that special experimental techniques had to be developed, including pyrometry[22], and methods of crucible preparation[23]. The investigation of chromium production by electrolytic methods was also started at an early stage and has continued up to the present time. Over this period there has been a steady improvement in the quality of the product, the current "standard" grade containing 0·01 per cent oxygen, 0·002 per cent nitrogen and practically no metallic impurities[24]. Work is now aimed at improving the economics of chromium production by substantially increasing the efficiency of the electrolytic process.

Since 1954, increasing emphasis has been placed on developing alloys and determining properties appropriate to the turbine blade application. Thus, work is being done on creep resistance in the range 900°—1,000°C (using in the first instance compression creep testing machines), hot hardness, scaling and surface protection, and methods of forming the alloys into the required shapes.

While it is not possible to present comprehensive creep data in a single diagram, Fig. 44 illustrates the comparative creep performance of high-grade commercial materials, and some A.R.L. chromium alloys are capable of showing comparable creep resistance at temperatures 100° to 200°C higher. If the test temperature for the commercial alloys is raised to 950°C, they exhibit minimum creep rates 10 to 100 times faster than do the experimental materials, and thus fail much sooner.

Attempts have been made to shape some of the stronger chromium alloys by modifications of commercial techniques. Considerable success has been achieved in hot-working the alloys, and machining and grinding do not appear to present any insuperable obstacles. On the other hand, it seems that melting and casting are always likely to require special equipment and techniques (*e.g.* argon-arc furnaces, now in semi-commercial use in U.S.A. for producing molybdenum).

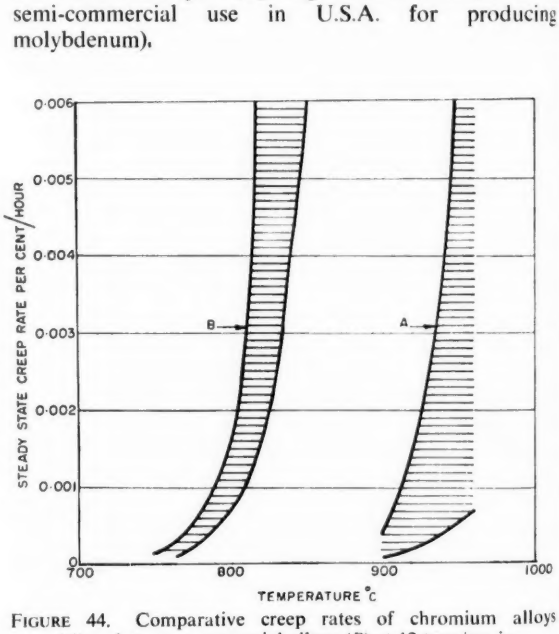



FIGURE 44. Comparative creep rates of chromium alloys (*A*) and strong commercial alloys (*B*) at 12 tons/sq. in.

FIGURE 45. Examples of ductile chromium.

Much remains to be done before the alloys can be regarded as fully evaluated. To this end, thermal shock, tensile creep and hot fatigue tests are projected in the near future, followed by tests in an experimental turbine rig.

Another important property being investigated is the ductility of chromium alloys at ordinary temperatures. It is desirable that any high-duty engineering material should show a certain minimum of ductility. Work at A.R.L. over the past three years[25, 26, 27, 28] has resulted in pure chromium being produced for the first time in a form which is ductile at room temperature. Furthermore, the extent of the ductility is of engineering significance; for example, values of 20 per cent elongation in a room-temperature tensile test have been obtained. Fig. 45 shows examples of ductile chromium.

An evaluation has been made of the factors governing the ductility of chromium. They fall into three main categories: (*a*) purity, (*b*) surface condition, and (*c*) metallurgical structure. Of these, the most important would appear to be purity and it has been shown that extremely small amounts of nitrogen (0·02 per cent or less) present in solution, can have a catastrophic effect. The effect of $N_2$ on the temperature at which the ductile-to-brittle transition occurs is shown in Fig. 46.

The foregoing work has been a necessary preliminary to the main problem of ductility in useful chromium-base alloys. Dilute chromium-base alloys have already been produced which are ductile at room temperature, and this has been achieved by making use of the techniques developed for pure chromium. There is every confidence that similar success will be obtained with the more highly alloyed materials.

The progress of the chromium project has been sufficiently encouraging for the Supply Department to enlist the aid of a second laboratory and, since 1954, the work has been done as a joint project by A.R.L. and the Defence Standards Laboratories, in which the latter establishment is concentrating on the technical problems of melting and working the alloys.

## Combustion Stability and Flame Out

I come now to the second turbine investigation. The Australian team which was sent to the U.K. during the war to assist in the development of jet engines, brought back an interest in combustion research. One of the members felt that the cut-and-try approach to combustor design could be improved.

The various zones of a combustion chamber which are separated by baffles, colanders and orifices of various sorts, connect with one another so closely that a variation in one air flow affects all the others. Thus, it is extremely difficult to separate out the effect of any one parameter. We therefore built what is known as the multi-air supply rig, in which the air flow to the different sectors of a combustion chamber are separately controlled and metered so that any one may be varied without affecting all the others. This has given a detailed insight into the general effects of flow variations, but the most valuable result has been the demonstration of the importance of air flow conditions very close to the fuel spray nozzle. It is in this region that a " pilot flame " is maintained and changes in the distribution and direction of fuel and air flows can have large effects on the general stability and efficiency of combustion. Air is normally fed through a shroud around the nose of the fuel nozzle for the dual purpose of cooling and elimination of carbon deposits on the front of the atomiser; this small air flow which intimately mixes with the fuel spray was found to have a predominant effect on the placement of fuel within the combustor, and hence on the nature of combustion. It was found that alteration of the momentum or direction of this air flow could cause a change from a fully developed flame of high efficiency and intensity to a core-shaped flame of low efficiency, but of great stability. The region between the two regimes was characterised by unstable transitions between the two modes of combustion, and this was found to be one cause of combustion " rumble ". This work was taken up by one engine firm who were able to " tailor " the characteristics of shroud geometry and fuel nozzle characteristics to give the desired high intensity, high efficiency combustion without rumble at cruising r.p.m. conditions, while retaining the high stability type of flame at lower speeds.

The conditions close to the fuel atomiser had been shown to have such a vital effect on combustion stability that attention was given to their effect on the

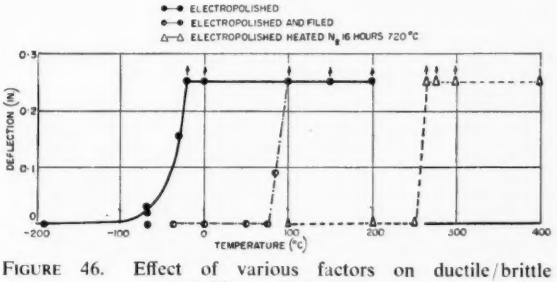



FIGURE 46. Effect of various factors on ductile/brittle transitions of chromium.

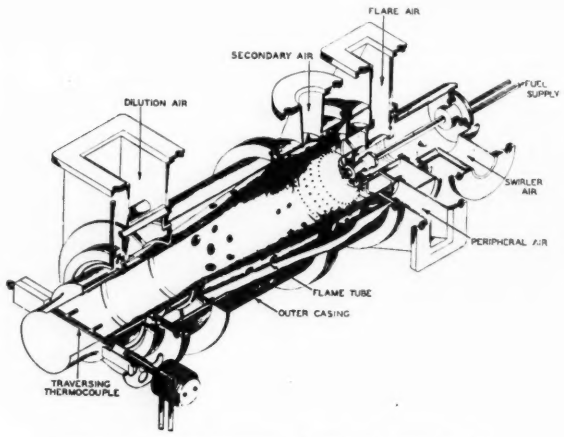



FIGURE 47. Arrangement of multi-air supply rig.

urgent problem of flame-out of engines at altitude. Some improvement of combustor characteristics was attained by alteration of shroud geometry, but the most dramatic results were obtained when pure oxygen was injected into the primary zone; in this way the weak extinction limits were extended tenfold while rich extinction, which can occur during a compressor surge, was virtually suppressed. These results have been attained both in atmospheric pressure rig tests and at simulated altitudes of 40,000 ft. The oxygen flows necessary to produce this result are so small that it is quite feasible to supply oxygen continuously to an engine during flight. The implications of these results are so important that we are arranging to make flight tests of an engine equipped for continuous oxygen injection.

Continuous oxygen injection may have important applications in the design of new engines. The volume of a combustion chamber is governed by altitude conditions, where the rate at which chemical combustion of fuel and oxygen can occur is the controlling process. Thus, by enriching the air with oxygen a desirable reduction in size of the combustion chambers can be achieved. A theoretical study has shown that substantial reductions in engine frontal area for a given thrust can be made in this way. There is even a small reduction in weight in spite of the fact that oxygen and associated storage and control equipment must be carried.

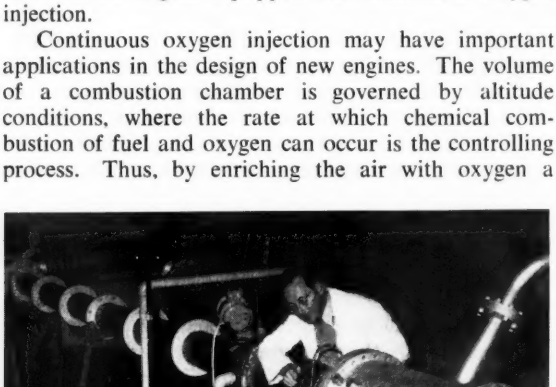


FIGURE 48. Multi-air supply rig in use.

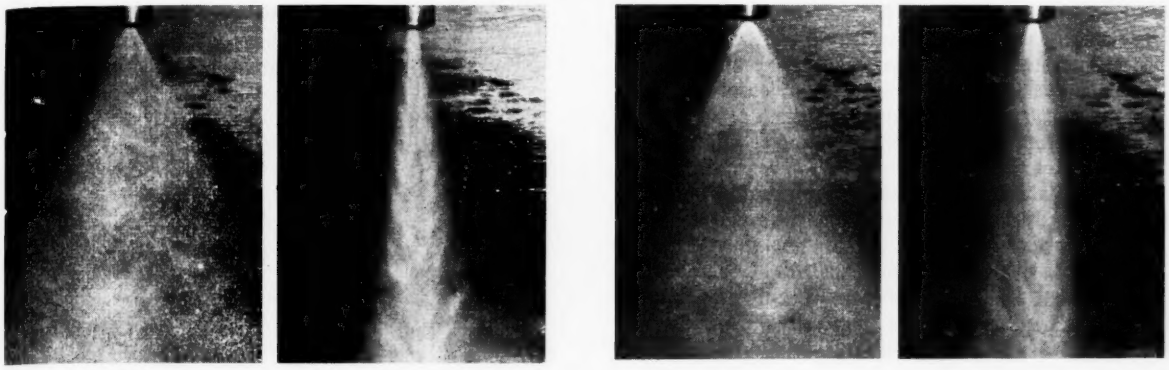
The ignition of combustion systems at altitude is also an important problem and the results of the investigations I have just mentioned have been applied to the design of a new type of igniter, which has been provisionally patented. In this ignition the spark is formed close to the most stable region of combustion by an annular discharge gap surrounding the main fuel nozzle and shroud. The use of low tension, high energy discharge is expected to preclude any trouble due to carbon deposits. Preliminary tests indicate that this device should give ignition right up to the extinction limits of the combustor and is particularly effective where continuous oxygen injection is practised. Very stable propagation of the flame is obtained when the fuel flow is turned up after initial ignition. An experimental unit, interchangeable with a standard atomiser, is being tested at present.

## Human Factors

Study of human factors in design and operation, or human engineering as it is sometimes called, is quite a new activity in Australia, although this form of research is well advanced in other parts of the world. A Group to study human factors was initiated at A.R.L. as the result of a joint request from the Department of Civil Aviation, the R.A.A.F., and the industry. Only the smallest of beginnings has been made by concentrating on one problem which represents the largest single cause of aircraft accidents and incidents—the human judgment in the vertical plane on final approach to landing. It seemed to be an appropriate subject for research since, after 50 years of powered flight, there is no accepted theory on the means of making visual judgments about the progress of an approach to landing, nor orthodox training in this task. The research is being done by the Aeronautical Research Laboratories in conjunction with officers of the Department of Civil Aviation.

Analysis of landing accidents indicates that errors in range of the touch-down point occur in clear, as well as in instrument weather, by day as well as by night. A preliminary study[29] has been made both of the information required by the pilot for judging the initiation and holding of the required approach method, and of the visual information available to the pilot in various circumstances. This has shown that in some conditions of restricted visibility, notably in the absence of a visual horizon (due either to weather or terrain) there is little redundancy of information, and so the best use must be made of the visual information which is available.

Already in this research a questionnaire of civil and service pilots and instructors has brought forth some interesting information on methods of judgment used on



Low fuel flow.

(1) Low fuel, low shroud flow. Coarse atomisation, medium spray angle, giving low efficiency, small flame.

(2) Low fuel, high shroud flow. Fine atomisation, narrow spray angle, giving medium efficiency core flame.

High fuel flow.

(3) High fuel, low shroud flow. Finer atomisation, wide spray angle, giving high efficiency fully developed flame.

(4) High fuel, high shroud flow. Very fine atomisation. narrow spray angle, giving medium efficiency core flame.

FIGURE 49. Effects of shroud air flow and fuel flow on shape and quality of a fuel spray.

final approach and on the diversity of training in this unique and difficult judgment.

Experiments are being planned to measure both in the field and on laboratory simulators the relative importance and sensitivity of the various visual judgments and the degree to which they can be improved, either by training or by visual aids mounted on the ground or in the cockpit.

A new instrument has been proposed for displaying in front of the pilot an artificial horizon superimposed on the natural horizon, whether this is visible or not, with a scale of angles of depression below it. This image will be formed at infinity by reflection in the windshield in the manner of a reflecting gunsight. Other displays, moving in relation to this, show the flight path of the aircraft and its relation to the I.L.S. beam. By thus providing the pilot with both position and heading information, it is hoped that he will be assisted to make precise approaches without a change of technique, in both clear and restricted visibility conditions, without having to look inside the cockpit at the critical stage of the approach when he is searching for, and identifying, the runway. Moreover, it shows the pilot where in his field of vision the runway will appear on break-through. We hope to try out this approach sight soon by modifying a gyro gunsight and coupling it to the other flight instruments.

## Research at Universities

While Australian Universities are active in many fields of research, aeronautical research is undertaken by only a small number of Universities and technical colleges. Several have wind tunnels, and gas turbine experiments on a small scale are made in some of the Mechanical Engineering Departments. However, the scale and volume of this research is very minor except at the University of Sydney, where a strong research group has grown up under Professor A. V. Stephens*. This group has the support of the Commonwealth Government in the shape of financial grants and staff seconded from the Aeronautical Research Laboratories of the Department of Supply. Substantial contributions to knowledge have been made in low speed aerodynamics and in the theory of structures but, as I must be selective, I propose only to describe the group's newest venture, supersonic research.

In April 1952, the University of Sydney embarked upon a programme of supersonic research, with the

*Professor Stephens has now accepted the new Chair of Aeronautics at Belfast University.

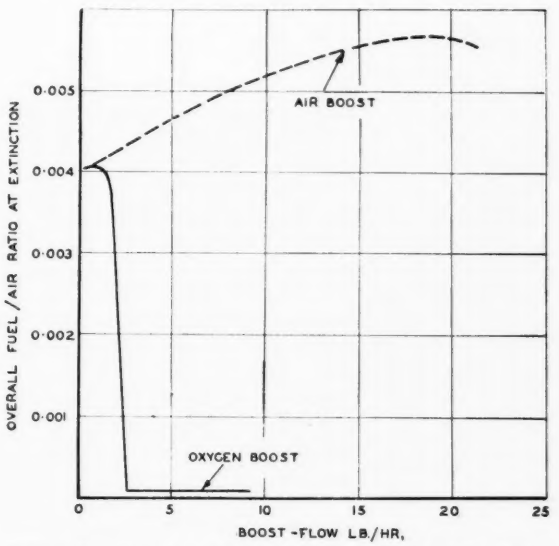



FIGURE 50. Variation of extinction limit of Typical Combustor with Oxygen and Air Boost.

assistance of a contract from the Department of Supply. Under the contract the University undertook to build a small intermittent supersonic wind tunnel and to study the technique of operating it. The object was to build up staff and facilities for supersonic work at Sydney and to provide information which would be of value to those designing and using large-scale equipment of a similar nature at the Weapons Research Establishment at Salisbury. In view of the emphasis on guided weapons in the Australian defence programme, it was clearly desirable that Australian students of aeronautical engineering, many of whom subsequently find employment in government research stations and firms designing missiles, should have a thorough training in both theoretical and experimental supersonics. Apart from this a University research team specialising in supersonics could be expected to make a worthwhile contribution to the art in its present state of development.

Detailed design of a supersonic tunnel began in April 1952 and the completed tunnel has been in operation since July, 1954. It is of the intermittent blow-down type with 6 in. × 3 in. working section for Mach numbers between 1·5 and 4, and Reynolds numbers between $0{\cdot}4 \times 10^6$ and $2{\cdot}5 \times 10^6$ per inch model chord. The tunnel incorporates a temperature recovery unit to keep the Reynolds number constant during runs. This unit was tested carefully and shown to satisfy the requirements of tunnel operation[30] and seems to be the first such unit in operation.

The satisfactory design of suitable nozzles entailed a considerable amount of theoretical work. For the first time anywhere a nozzle was built which had been designed by Hodograph theory[31]—this particular nozzle produces a Mach number of 2·41. The method generally used for nozzle design is the numerical method of characteristics and an earlier investigation into analytical solutions of problems of two-dimensional supersonic flow in collaboration with Aerodynamics Division, A.R.L.[32], led to an investigation of the accuracy of this method. The laws of growth and accumulation of errors were established and it was shown how the computation can be planned in advance for any chosen accuracy, with a considerable reduction of labour[33].

A new method of estimating turbulent boundary layer growth has been developed[34] and in conjunction with a theory of supersonic perturbations of nozzle flows[35] yields a simplified practical approximation for the boundary layer thickness. The perturbation theory has also been used to obtain detailed estimates of the effect of changes in tunnel Reynolds number and of manufacturing tolerances on liners on the velocity distribution in the working section. Arising from this it was shown that even with the best nozzles in use at present, corrections for the non-uniformity of flow are desirable[36]. A good deal of work has also been devoted to problems of experimental technique. The use of strain-gauge balances in the tunnel is impeded by practical difficulties, due to the small model sizes. A theoretical investigation therefore has been made into

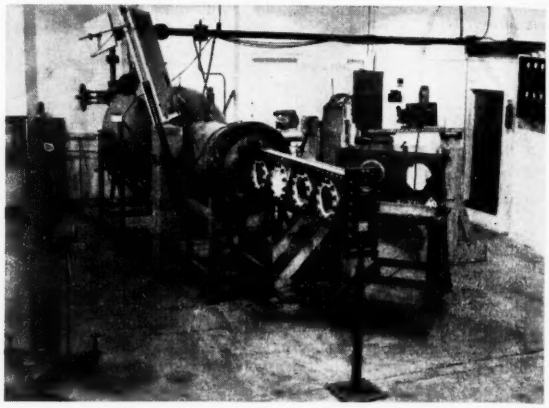


FIGURE 51. 6 in. × 3in. Supersonic wind tunnel at Sydney University.

the question of the accuracy with which aerofoil drag can be measured by a pressure traverse[37]. A means was found of balancing the errors arising from the impossibility of measuring the static pressure near shocks and from omission to measure the stagnation temperature distribution and, in general the outlook is felt to be quite hopeful. However, further work on the measurement of stagnation pressure is required and, as in the U.K., attention has shifted to the problem of producing a supersonic shear flow on a sufficiently large scale. A theory was therefore developed for the design of a wall shape which would convert a uniform supersonic stream into a chosen parallel shear flow at near uniform pressure[38].

The china-clay film technique of indicating boundary layer flows has been extensively studied[39]. It is suitable for intermittent tunnels and can be used to obtain indication not only of the boundary layer stream line pattern, transition and separation, but also of shock incidence on solid surfaces. In fact the technique has been shown to be not only much cheaper, but more effective, than pressure plotting for the detection of weak shocks.

The first quantitative supersonic experiments in Australia have provided valuable lessons in technique. Progress in pressure plotting and china film indication have made it possible to show that the present non-uniformity of flow in the test-section is almost entirely three-dimensional and that the Sydney tunnel is exceptionally sensitive to such effects.

## Concluding Remarks

I have now come to the end of my survey of aeronautical activity in Australia. I have tried to cover a broad canvas—too broad, it may be thought—yet, it is all relevant to the theme of this lecture if one seeks to find ways of strengthening the bonds of the Commonwealth, and especially the bonds between the United Kingdom and Australia.

Summarising the impressions I have tried to convey, we find in Australia:—

A wonderful country for flying and for the use of the aeroplane in almost every kind of role;
an extremely virile commercial air transport system comparable in size to that of the U.K.;
the aeroplane widely used for the development of backward areas;
agricultural applications and private flying only moderately developed;
a guided missile range and supporting facilities second to none;
aeronautical research facilities capable of making substantial contributions to any development programme;
a highly developed aircraft industry which appears to be destined to sink into the purely passive role of maintenance.

The order in which these observations are given is not significant; they merely follow the text.

Turning now to the British Commonwealth aspects, we find the following co-operative arrangements:—

*The Woomera Rocket Range*

This is a perfect example of a co-operative effort between the U.K. and Australia in which great difficulties due to the geographical separation of the two countries have been overcome by the will to make things work. A very gratifying facet of the arrangement is that Australia has undertaken the development and production of the pilotless target aircraft used in the trials.

*The Commonwealth Advisory Aeronautical Research Council*

This body is open to membership to all countries of the British Commonwealth, but while six countries have attended meetings, only the U.K., Canada and Australia have achieved a real measure of co-operation in aeronautical research. Within these smaller limits a real strengthening of the bonds of the Commonwealth has been achieved, and it is our hope that the work will be continued and, in time, expanded by other countries participating. The real obstacle to progress is that aeronautical research has not yet been organised on a national scale in any of the other Commonwealth countries.

*Licencing Agreements and the Setting up of Branches of U.K. Firms in Australia*

This form of co-operation has been in being since de Havilland Aircraft first opened a branch in Australia in 1932, and many of the famous British firms now have satellite factories here. The Rocket Range is giving a great impetus to this liaison. Licences for manufacture of aircraft and engines have been negotiated with Australian firms, but we have not progressed as far as Canada in that no design effort is decentralised in the way Avro-Canada has been formed. Guided weapons and special aeroplanes for particular purposes would be suitable directions in which to begin.

Australia is geographically close to large populations of Eastern people who have few aircraft production facilities. It could logically become a source of supply under a suitable licencing arrangement.

*The Kangaroo Service Between London and Sydney*

This is a truly co-operative effort between B.O.A.C. and QANTAS Empire Airways which, in great harmony, operate the longest commercial air route in the world. The basis of this co-operation is mutual trust and a will to work together. Sir Hudson Fysh, in his speech in London to celebrate the 21st anniversary of the B.O.A.C.-Q.E.A. partnership, recalled the original Heads of Agreement as a most remarkable document which would never have proved workable between other than Britishers. Clause 26, the square deal clause reads:—

> "It is the intention of both parties that each shall have a 'square deal' in the sense that that expression is understood by fair and reasonable minded men".

It will be noticed, and it is a matter for regret, that all but one of these co-operative arrangements are on a U.K.-Australia basis.

What more can be done? His Royal Highness, the Duke of Edinburgh, pleaded the case for studying the special needs of the Commonwealth countries and developing the right kind of aeroplane. This is certainly true of many aspects of Australian aviation; in agricultural, freight, private flying and flying in difficult areas like New Guinea. Performance must suit the semi-tropical conditions and price is a major consideration. Intelligent market research may well pay dividends in this field.

Finally, I would like to leave a thought suggested by one of the aircraft operators. British commercial aircraft have only been moderately successful in capturing world markets, despite the brilliant success of the Viscount. The British designer is second to none and the industry has a long record of military successes. The weaknesses, and here I tread upon dangerous ground, are two: firstly, the long period from the first conception to the aircraft entering airline service; and secondly, lack of appreciation of the needs of operators in other countries.

Aircraft often take seven or eight years to perfect; this was true of the Viscount, whereas the Convair took only four years by intensifying the development stage. Australian airlines, by reason of their wonderfully suitable conditions of operation, have higher utilisations of aircraft than any other country in the world. No firm's tests will ever disclose the weaknesses which airline operation will find; sheer hours on one unit, whether aircraft or engine, are a searching test, total hours on a number of units being much less significant. Consequently, the French, in order to shorten the development period of the Caravelle, have put a prototype into simulated passenger service with Air France, although actually the aircraft only carries freight. Could not British types, quite early in their development, be handed to an Australian operator to find the bugs? At

the moment, new aircraft are not seen in Australia until they are regarded as perfect.

Australian operators would also be glad to help in the specification and conception stages of projected designs. They have long experience of aircraft operation under highly competitive conditions and are familiar with both British and American types and with the thinking of both countries. I believe that, if consulted, they would bring a new viewpoint to bear, a viewpoint which might well ensure the acceptance of the type in a much wider market than the European.

I trust that nothing I have said will be misinterpreted. I believe that I speak for Australia when I say that she values the ties of kinship and blood very highly and that if there is any way in which she can help to strengthen the bonds of the British Commonwealth, she can be counted on to play her part.

## Acknowledgments

I have received a great deal of help in the preparation of this paper by discussions with the following persons:—

Dr. R. R. Shaw, Mr. J. S. Arthur and Mr. A. J. Livingstone of the Department of Civil Aviation; Mr. I. Grabowski and Mr. J. A. North of Australian National Airways; Sir Hudson Fysh of Qantas Empire Airways; Mr. J. L. Watkins of Trans-Australia Airlines; Mr. Fred Hoinville of the Aircraft Operators and Pilots Association and Mr. C. A. Patching of the Gliding Federation of Australia; Air Vice-Marshal Scherger, Air Vice-Marshal E. C. Wackett and Wing Commander P. J. Wood of the Royal Australian Air Force; Mr. B. M. Woodful and Mr. I. Fleming of the Department of Aircraft Production; and Mr. E. Jones of Commonwealth Aircraft Corporation.

I am also indebted to Mr. H. J. Brown, Controller, and Mr. F. P. O'Grady of the Weapons Research Establishment, for information about the Woomera Range.

Finally, I must gratefully acknowledge the very considerable assistance of a number of members of the staff of the Aeronautical Research Laboratories, who have prepared research and other material, diagrams and photographic illustrations.

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## VOTE OF THANKS

MR. JONES: It was not the custom to have a discussion following this series of Lectures. Instead he would ask Professor Collar to propose a vote of thanks to the lecturer and Mr. Handel Davies to second that vote of thanks.

PROFESSOR A. R. COLLAR (*Fellow*): There were, he was sure, well accepted and very well respected ways in which a vote of thanks on an occasion such as this should be proposed. He had no doubt, therefore, that he was going to offend against all the canons as to what should be done by introducing a personal note right at the beginning.

Mr. Coombes mentioned in his lecture that in 1908 George Taylor founded an aircraft factory in Australia. It so happened that he was born in the same year. He did not think there was any connection between the two events, but however that might be, nearly forty years later the Council of this Society honoured him with the George Taylor (of Australia) Gold Medal. Shortly afterwards he received a very nice letter from Mrs. Florence Taylor, the widow of George Taylor; and since within the year he found himself in Sydney, he thought it was incumbent upon him to call and see her. Accordingly, he found his way to the office in Sydney, from which she conducted an extraordinarily large amount of business, being a journalist, an engineer, and a tremendous variety of other things. He found an extremely energetic lady of 70; and the conversation went something like this:

"May I introduce myself, Mrs. Taylor, my name is Collar."

"Oh, you are Professor Collar. How do you do. Very pleased to see you. Are you doing anything this evening? No? That's fine. Well, there is a meeting this evening of the Soroptimists' Club of New South Wales, of which I am President, and we shall be very happy for you to come and address us."

Just like that! So within an hour or so behold him addressing a gathering of between 150 and 200 women; and he was bound to say that the present occasion caused him very much less trepidation!

Well, that was an occasion when an Australian aeronautical function had him on his feet; and here was another. He must add that the function which found him in Sydney then was the first meeting of the Commonwealth Advisory Aeronautical Research Council, of which the President spoke earlier, and to which Mr. Coombes had referred so often in his lecture. That body, as the lecture had clearly shown, was extremely well worth while. The co-operation that had gone on in aeronautical research was, he thought, something to be wondered at, in view of the distance which separated Australia from the United Kingdom. He well remembered being very impressed at that time by the potential of Australia, and perhaps in particular by the air-mindedness (or perhaps he should say in deference to Mr. Peter Masefield, the air-faring outlook) of Australia. Being at one of the airports of Melbourne or Sydney was just like being at Paddington or Liverpool Street. The whole of the population of the continent of Australia, when travel was necessary, appeared to go by air and to do it purely as a matter of course.

There, then, was the potential, and there was the opportunity for Commonwealth co-operation in the research field; and the fruits of that co-operation had been described to them that evening, so far as they had gone at the moment; and he thought they were quite remarkable. The fatigue problem: a history of research into fatigue that was longer and in some respects greater in content than any research that had been carried on elsewhere. Aerodynamical research: he knew certain people who would give their ears to have had an active finger in the pie of some of the things that had gone on in the Australian Aeronautical Research Laboratories. And he had himself noticed an increasing flow of Australian literature of no mean competence in the field of aeroelasticity. Then there was the co-operative effort of the guided weapons field. All this added up to a considerable achievement; but unfortunately there was the other aspect to which Mr. Coombes had referred. Was it not in fact possible for something to be done to keep the aeronautical industry alive in Australia? And here he must confess that reading the paper he was reminded (here he was riding a favourite hobby-horse) that the great thing in the history of the British Commonwealth of Nations had been transport. Yet despite the lessons of our history they were, he was sure, devoting far less attention than was proper in this country and throughout the Commonwealth to transport aircraft. Was there not here a vitally important field in which the United Kingdom and the Australian Governments could get together and do something which would ensure the continuance of the industry in Australia in the manner in which Mr. Coombes had suggested it should be continued?

These, Mr. President, were a few thoughts prompted by the lecture, which he was sure everybody would agree had been an extraordinarily interesting and extremely well illustrated lecture: a lecture delivered with all the charm which one would expect from Laurie Coombes. A lecture, moreover, that showed his mastery of his subject—a mastery which stemmed from an absorbing interest in it. They had all listened, he was sure, with close attention and delight, and it now gave him the very greatest pleasure to propose a most hearty vote of thanks to Mr. Coombes.

HANDEL DAVIES (*Fellow*): At this time when their ties with the Commonwealth were being subjected to a certain amount of strain in various directions it had been a very great pleasure and privilege to listen to someone who had done perhaps more than anyone to strengthen their ties with the Commonwealth of Australia in the aeronautical field. And if any of them had previously entertained any doubts whether Australia could make a major contribution to progress in aeronautics then assuredly those doubts had been dispelled by what they had heard that night.

As the President had said, it was not customary to have a discussion on the Commonwealth lecture. There was,

however, just one thing he would like to say about the lecture itself and that was to suggest that perhaps Mr. Coombes had been a little too modest both about his own achievements and the achievements of the country which he had made his own for the past 17 or 18 years and he would like to quote one example which illustrated this because it happened to be one with which he had a slight association himself. He referred to the flight tests which were made on the Griffiths suction wing. Those experiments in flight were, he could assure them, extremely difficult, and they in this country embarked at about the same time on a complementary series of experiments in flight on a different aircraft and in a somewhat different way. He would like to say here and now that the skill and recourse and powers of organisation which the Australians showed in performing those experiments were outstanding in every way and they bowed to their superiority. They succeeded in those experiments in a way which he thought was quite astonishing and the paper itself merely made a passing reference to what was, he thought, an achievement for which they could well be proud.

Finally, perhaps he might be permitted a personal note with regard to the lecturer himself. It was as it happened exactly 20 years ago, this very day, as he found on consulting his diaries for 1936 that he met Mr. Coombes for the first time. Mr. Coombes would have forgotten this of course because he was merely a newcomer to the R.A.E. being shown round the high spots of the Establishment and he had a vivid recollection of being shown round the seaplane tank and being introduced to Mr. Coombes who was in charge. He recalled two strong impressions; one was how youthful he seemed to be in charge of such an important piece of equipment and also the human qualities which he showed to the very inexperienced staff who were serving with him.

Well, two years later Mr. Coombes left the R.A.E. to go to Australia and he thought the status to which he had raised aeronautical research in Australia, which had been so well illustrated by his lecture, was sufficient tribute to his qualities as a scientist and as a leader.

It was therefore with the greatest pleasure that he seconded the vote of thanks to him.

E. T. JONES: He would like to add his own personal thanks to Mr. Coombes for the hard work he had put in in preparing his paper and for coming over and delivering it as he had done.

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Following the Lecture a Dinner was given at the offices of the Society, 4 Hamilton Place, London, W.1, at which the following were present:—

Dr. A. M. Ballantyne, T.D., B.Sc., Ph.D., Hon.F.C.A.I., A.F.I.A.S., F.R.Ae.S.; Secretary of the Royal Aeronautical Society. Professor A. D. Baxter, M.Eng., M.I.Mech.E., F.R.Ae.S.; Member of Council of the Royal Aeronautical Society; Professor of Aircraft Propulsion, College of Aeronautics, Cranfield. The Rt. Hon. Nigel Birch, O.B.E., M.P.; Secretary of State for Air. Mr. E. C. Bowyer, C.B.E.; Director and Chief Executive, Society of British Aircraft Constructors. Air Chief Marshal Sir Dermot A. Boyle, K.C.V.O., K.B.E., C.B., A.F.C.; Chief of the Air Staff, Air Ministry. Major G. P. Bulman, C.B.E., B.Sc., F.R.Ae.S.; Member of Council and Honorary Treasurer of the Royal Aeronautical Society; Director of Construction and Research Facilities, Ministry of Supply. Sir Frederick Brundrett, K.C.B., K.B.E.; Chairman, Defence Research Policy Committee and Scientific Adviser to the Minister of Defence.

Sir Sydney Camm, C.B.E., F.R.Ae.S.; Past-President of the Royal Aeronautical Society, Director and Chief Designer, Hawker Aircraft Ltd. Professor A. R. Collar, M.A., D.Sc., A.F.I.A.S., F.R.Ae.S.; Member of Council of the Royal Aeronautical Society; Sir George White Professor of Aeronautical Engineering, University of Bristol. Mr. H. Constant, C.B.E., M.A., F.R.S., F.R.Ae.S.; Director, National Gas Turbine Establishment. Mr. L. P. Coombes, D.F.C., F.I.A.S., F.R.Ae.S.; 1956 Lecturer; Chief Superintendent, Aeronautical Research Laboratory, Melbourne; President, Australian Division Royal Aeronautical Society. Vice-Admiral W. T. Couchman, C.B., C.V.O., D.S.O., O.B.E.; Deputy Controller of Aircraft, Ministry of Supply.

Mr. Handel Davies, M.Sc., A.F.I.A.S., F.R.Ae.S; Member of Council of the Royal Aeronautical Society; Deputy Director—General Aircraft Research and Development (Future Systems), Ministry of Supply. Mr. L. J. Dunnett, C.M.G., Deputy Secretary (A), Ministry of Supply.

Mr. G. R. Edwards, C.B.E., B.Sc., F.R.Ae.S.; President-Elect of the Royal Aeronautical Society; Managing Director, Vickers-Armstrongs (Aircraft) Ltd.

Mr. G. W. H. Gardner, C.B., C.B.E., B.Sc., F.R.Ae.S.; Director, Royal Aircraft Establishment. Mr. H. H. Gardner, B.Sc., F.R.Ae.S. Member of Council of the Royal Aeronautical Society; Chief Designer, Guided Weapons, and Special Director, Vickers-Armstrongs (Aircraft) Ltd. Sir Harry M. Garner, K.B.E., C.B., M.A., F.R.Ae.S.; Member of Council of the Royal Aeronautical Society.

Mr. S. Scott Hall, C.B., M.Sc., D.I.C., A.F.I.A.S., F.R.Ae.S.; Scientific Adviser, Air Ministry. Mr. R. E. Hardingham, C.M.G., O.B.E., F.R.Ae.S; 1952 Lecturer; Secretary and Chief Executive to the Air Registration Board. Mr. P. A. Hearne, D.C.Ae., D.L.C., Grad.R.Ae.S.; Member of Council of the Royal Aeronautical Society; Helicopter Project Engineer, Project and Development Branch, British European Airways.

Lord Hives, C.H., M.B.E., LL.D., D.Sc., F.R.Ae.S.; Chairman, Rolls-Royce Ltd. Mr. F. W. Hooten, B.Sc., B.E., A.F.R.Ae.S.; Scientific Liaison Officer, Australia House.

Mr. Colin G. Jones; Service Engineer, Sperry Gyroscope Co. Ltd. Mr. E. T. Jones, C.B., O.B.E., M.Eng., F.R.Ae.S.; President of the Royal Aeronautical Society; Director General of Technical Development (Air), Ministry of Supply. Air Marshal Sir Owen Jones, K.B.E., C.B., A.F.C., B.A., D.I.C., M.I.Mech.E., F.R.Ae.S.; Member of Council of the Royal Aeronautical Society.

Mr. E. R. Knight; London Manager, Australian National Airways Pty. Ltd. Lord Knollys, G.C.M.G., M.B.E., D.F.C.; Chairman, Vickers Ltd.

Mr. B. P. Laight, M.Sc., A.M.I.Mech.E., F.R.Ae.S.; Member of Council of the Royal Aeronautical Society; Chief Designer Blackburn and General Aircraft Ltd. Mr. V. F. Letcher; Senior Representative, Departments of Supply and Production, Australia House.

Mr. P. G. Masefield, M.A., Hon.F.I.A.S., F.R.Ae.S.; Vice-President of the Royal Aeronautical Society; Managing Director, Bristol Aircraft Ltd. The Rt. Hon. R. Maudling, M.P.; Minister of Supply. Mr. M. B. Morgan, M.A., F.R.Ae.S.; Member of Council of the Royal Aeronautical Society; Deputy Director, Royal Aircraft Establishment. Dr. E. S. Moult, Ph.D., B.Sc., M.I.Mech.E., F.R.Ae.S.; Vice-President of the Royal Aeronautical Society; Director and Chief Engineer, de Havilland Engine Co. Ltd. Sir Cyril Musgrave, K.C.B.; Permanent Secretary, Ministry of Supply.

Mr. F. M. Owner, C.B.E., M.Sc.(Tech.), M.I.Mech.E., F.R.Ae.S.; Member of Council of the Royal Aeronautical Society; Deputy Chief Engineer, de Havilland Engine Co. Ltd. Air Marshal Sir Claude Pelley, K.C.B., C.B.E., M.C.; Controller of Aircraft, Ministry of Supply. Colonel R. L. Preston, C.B.E., A.F.R.Ae.S.; Secretary-General, Royal Aero Club. Captain J. L. Pritchard, C.B.E., Hon.F.I.A.S., Hon.F.R.Ae.S.; Former Secretary, Royal Aeronautical Society, 1925-1951.

Mr. N. E. Rowe, C.B.E., B.Sc., F.C.G.I., F.I.A.S., F.R.Ae.S.; Past-President of the Royal Aeronautical Society; Technical Director, Blackburn and General Aircraft Ltd.

Group Captain Salah-ud-Din; Air Adviser to the High Commissioner for Pakistan. Professor A. V. Stephens, M.A., F.R.Ae.S.; Past-President, Australian Division, Royal Aeronautical Society; The Chair of Aeronautical Engineering, The Queen's University of Belfast.

Mr. E. Turner; Chairman and Managing Director, Blackburn and General Aircraft Ltd.

Mr. C. F. Uwins, O.B.E., A.F.C., F.R.Ae.S.; President, Society of British Aircraft Constructors; Chairman, Bristol Aircraft Ltd.

Mr. A. O. M. Vialls, B.Sc., T.M.I.A.S., A.F.R.Ae.S.; Member of Council, Southern Africa Division, Royal Aeronautical Society.

Sir Hubert Walker, C.B.E., M.I.C.E.; 1953 Lecturer. Dr. P. B. Walker, C.B.E., M.A., Ph.D., F.R.Ae.S.; Member of Council of the Royal Aeronautical Society; Head of Structures Department, Royal Aircraft Establishment.

# JET EFFLUX — A SYMPOSIUM

A report was given, in the November 1956 issue of the Journal, of the Joint Conference held by the Royal Aeronautical Society and the Institute of Physics (Stress Analysis Group) at the College of Aeronautics, Cranfield, on 19th-21st September 1956. During the course of this Conference a Symposium on Jet Efflux was held under the Chairmanship of Dr. P. B. Walker, Head of the Structures Department, R.A.E. This Symposium was in the nature of a review of the practical experience gained in recent years, and formed a follow-up to the Symposium on Jet Noise held by the Society in 1953 (*see* the Journal of the Royal Aeronautical Society, April 1954, pp. 221-260). Papers on various aspects of jet efflux were given by:—Mr. M. O. W. Wolfe, D.I.C., Dr. R. E. Franklin, Mr. D. J. Mead, D.C.Ae., A.F.R.Ae.S., Dr. B. I. Clarkson, B.Sc., Grad.R.Ae.S., and Mr. K. W. Hetzel, A.F.R.Ae.S.

Summarised versions of these papers follow together with a summary of the discussion, which was reported by Mr. J. C. Simmons, M.Sc.(Eng.), Grad.R.Ae.S.

# The Structural Aspects of Jet Noise

by

M. O. W. WOLFE, D.I.C.

*(Head of Flutter and Vibration Division, Structures Department, R.A.E.)*

## 1. Introduction

The increase in jet engine thrust has been accompanied by an increase in the noise generated by the jet stream to such an extent that the associated noise pressures are now capable of exciting vibrations in an aircraft structure which are potentially dangerous from the fatigue aspect. Several examples of fatigue damage of this kind have appeared already on aircraft in this country and in the United States.

The noise generated by a gaseous jet arises principally from disturbances caused by high velocity gradients at the jet boundary. Classical theoretical work on noise generated in this way has been done by Professor Lighthill[1]. He introduced the concept of an "acoustic quadropole" as the elementary sound generator, and showed mathematically that the total acoustical power radiated by a jet varies directly as the eighth power of the jet exit velocity and the second power of the jet exit diameter. (In the corresponding relationship for noise pressure the exponent of the velocity is four). In a more recent paper Lighthill[2] has questioned the validity of his original assumption of a stationary distribution of acoustic quadropoles. For a moving distribution of acoustic quadropoles the exponent of the velocity in the total acoustic power relationship would be higher than eight.

The validity of the $V^8$ law has been examined experimentally by several investigators on model cold jets and on the hot jets of actual gas turbine engines. For moderate ranges of shear velocity the agreement with theory for remote field conditions has been found to be quite good.

There are, however, two important considerations here; the first is that the value of the velocity exponent "$n$" cannot remain constant as the shear velocity is increased to higher values because a condition would eventually be reached at which all the power of the engine would be propagated as noise. The other is that the oscillating air pressures observed in the very near field, that is to say at and within the jet cone boundary, are probably caused principally by hydrodynamic effects such as rapid velocity variations and momentum effects, conditions for which the Lighthill theory is not strictly applicable.

Since this region of the noise field is the really significant one from the aircraft structural aspect, a knowledge of jet noise conditions here is all important from the aircraft designer's point of view. It is unfortunate that this also happens to be the portion of the field for which there exists no adequate theoretical background to enable him to predict the intensity and quality of the noise for particular engine conditions.

We have, therefore, concentrated attention on this region in our preliminary experimental investigations at the Royal Aircraft Establishment and this paper is limited to a description of this work and its results.

## 2. General Characteristics of Jet Noise Spectra

The main characteristics of the noise spectra of a jet engine are shown in Fig. 1. The noise spectrum shown is a very typical one and was measured at a radius of 10 ft. from the nozzle of a Ghost "50" engine along a line at 30° to the jet axis when the engine was operating at an efflux velocity of 1,800 ft. per second. The sound pressure scale is in decibels and in lb. per sq. ft. (The decibel scale on all the figures is referred

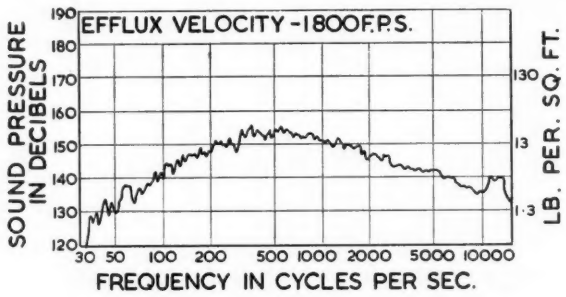


FIGURE 1. Sound pressure level spectrum for Ghost "50" at a point 10 ft. distant from the nozzle on a radius at 30° to jet axis.

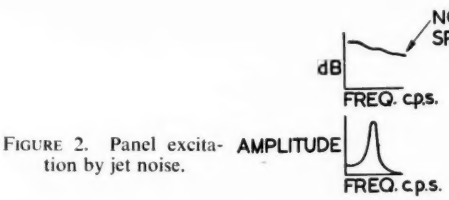


FIGURE 2. Panel excitation by jet noise.

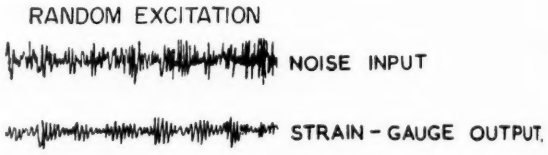


FIGURE 3. Response of panel.

to a threshold noise pressure of 0·0002 dynes per sq. cm.)

The main characteristics of note are the wide range of frequencies involved and the absence of marked peaks in the spectrum. The spectrum is of a continuous nature and the greatest pressures occur in the range 200 c.p.s. to 700 c.p.s., these pressures being in this case approximately 13 lb. per sq. ft., or 150 decibels.

## 3. Structural Response

The response of an aircraft structure consisting, for example, of the conventional skin panels, stringers and frames to "white" noise has been the subject of investigation in this country and in the United States.

A structure having discrete natural frequencies is frequency-selective in its response, for example an idealised single degree of freedom system would respond in a manner similar to that shown in Fig. 2. Here the "white" noise spectrum is shown in the top diagram and the panel response in the lower diagram. Measurements made at the R.A.E. of the strain spectra of panels subjected to jet noise have shown this characteristic very markedly. Typical response spectra show several peaks which are not apparent as such in the corresponding noise spectra.

Corresponding records of the noise excitation and the panel response are shown in Fig. 3. The difference in character of excitation and response is here clearly demonstrated.

In practice the actual damage caused by jet noise excitation is generally localised and is usually characterised by fatigue cracks in panels starting at rivet holes and propagating along the lines of the rivets and by failures in the cleating at stringer, frame skin joints.

An important feature of this process of fatigue damage is that because of the comparatively high frequencies involved, the rate of attrition is high and damage, if it is going to occur, usually occurs rapidly. It is therefore a condition of extremely low level fatigue. This fact, and the high frequencies involved have certain important implications which will be referred to later.

## 4. The R.A.E. High Level Noise Microphone

High intensity noise measurements at high frequencies and in the heated ambient conditions close to jet cone boundaries present an unusually difficult problem. It was therefore necessary to develop a special microphone at the R.A.E. for this purpose. This instrument is of the flat plate, variable gap condenser type and is effectively water-cooled. Views of the

FIGURE 4(*a*). Assembled view of R.A.E. Condenser Microphone.

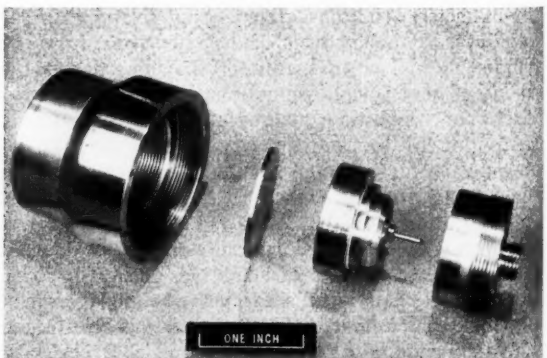


FIGURE 4(*b*). Exploded view of R.A.E. Condenser Microphone.

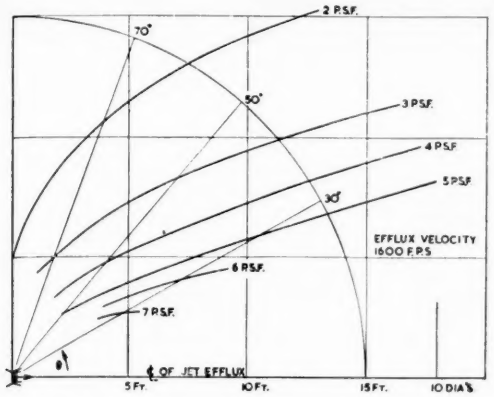


FIGURE 5. Constant overall sound pressure contours. Obtained from starboard outer engine (Ghost 50) on Comet G-ALYS.

instrument, exploded to show the constructional details and assembled, are shown in Fig. 4.

## 5. Experimental Work

The experimental work on jet noise at the R.A.E. has been done on de Havilland Ghost "50" engines installed in a Comet 1 aircraft. The engines were run with the aircraft on the ground and noise measurements were made over the full range of engine thrust.

### 5.1. NOISE PRESSURE DISTRIBUTION

The variation of noise intensity with position relative to the jet in the near field is shown in Fig. 5. Isobars of overall noise pressure are plotted in the diagram for the condition of 1,600 ft. per second shear velocity.

The distribution varies to some extent with shear velocity but this diagram is fairly typical of the range from 1600 to 1800 ft. per second on the Ghost engines. The variation in the nature of the spectra for different positions in the noise field relative to the jet orifice is shown in Fig. 6. In general, the higher frequencies are encountered close to the jet orifice; the lower frequencies tend to predominate in the more remote field.

The spectra vary also with the shear velocity and this is illustrated in Fig. 7 which shows spectra taken at identical positions in the field for three different values of shear velocity. As the velocity is raised the high frequency content of the noise spectra is increased.

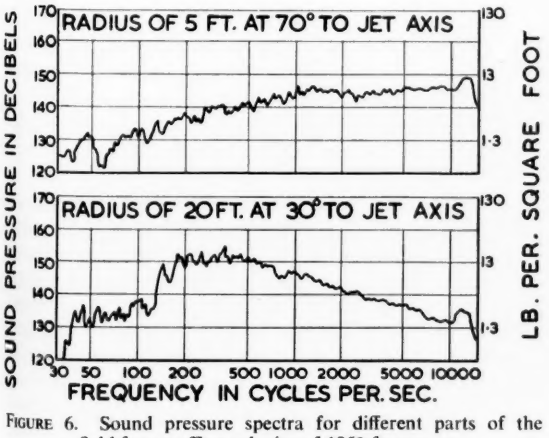
RADIUS OF 5 FT. AT 70° TO JET AXIS
RADIUS OF 20 FT. AT 30° TO JET AXIS
SOUND PRESSURE IN DECIBELS
LB. PER. SQUARE FOOT
FREQUENCY IN CYCLES PER SEC.

FIGURE 6. Sound pressure spectra for different parts of the field for an efflux velocity of 1850 ft. per sec.

### 5.2. THE VALUE OF THE VELOCITY EXPONENT "$n$"

The variation in the value of the index "$n$" in Lighthill's law: $-P \propto D^2 V^n$ has been deduced from the experimental results for various positions in the sound field, over a range of shear velocities varying from 400 to 1850 ft. per second.

The experimental results are plotted in Fig. 8. The curves show the variation of "$n$" along lines at several angles to the axis of the jet.

In the remote field the index approaches the Lighthill value of 4, but close to the jet boundary it falls to values as low as 1·6, showing that the assumptions of the theory are not valid for near field conditions. The experiments, however, cover only a very limited range of shear velocity and clearly, before any general conclusions can be drawn, this range must be extended to much higher values of velocity.

## 6. Conclusions

The question of structure response has only been mentioned briefly, mainly because the response of structures to random noise is a subject which is not yet properly understood. For example, in considering the structure response to jet noise it is necessary to take account of phase influences in the forcing spectrum in relation to the structure modes, in addition to the mechanical impedance properties of the structure itself.

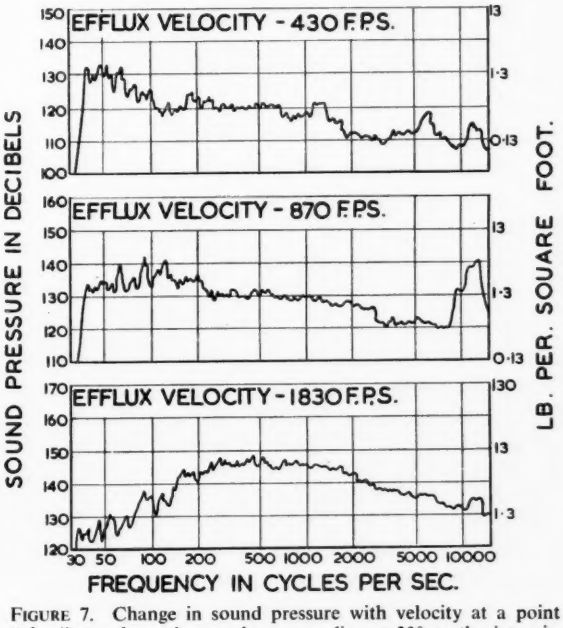
EFFLUX VELOCITY - 430 F.P.S.
EFFLUX VELOCITY - 870 F.P.S.
EFFLUX VELOCITY - 1830 F.P.S.
SOUND PRESSURE IN DECIBELS
LB. PER. SQUARE FOOT
FREQUENCY IN CYCLES PER SEC.

FIGURE 7. Change in sound pressure with velocity at a point 5 ft. distant from the nozzle on a radius at 30° to the jet axis.

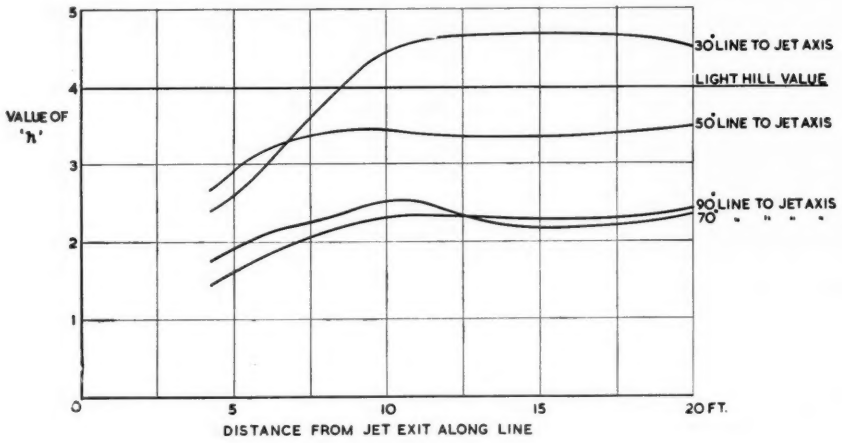


FIGURE 8. Acoustic pressure law index for velocities 400-1850 ft. per sec. Variation of "$n$" along lines at angles to the jet axis.

One can, however, draw certain general conclusions. The first is that since the excitation spectra are continuous there is not much hope of improving matters by detuning the structure to avoid resonance. It would therefore seem that stiffening the structure on broad strength considerations would be a more profitable approach. This would also raise its natural frequencies and, since the excitation spectra appear to be less intense at the higher frequencies, this should be beneficial. Structure damping is also probably more effective at higher frequencies.

This argument implies that the ratio of skin thickness to stringer and frame spacing should be as high as is compatible with other design considerations. There is already some evidence to show that this is so and, in particular the honeycomb sandwich type of construction, which represents an extreme example of this rule, appears to be good.

The other general conclusion that may be drawn is that since natural frequencies of the structure appear to be involved and the stresses are low by normal fatigue standards, considerable improvement may be gained by the introduction of even small amounts of damping. Here again a honeycomb sandwich type of construction would appear to be an obvious choice. Finally it should be mentioned that in this, as in all fatigue problems, careful avoidance of stress raisers in design is an obvious precaution.

## Acknowledgment

The author is indebted to the Chief Scientist, Ministry of Supply, for permission to publish this paper. The illustrations are Crown Copyright reserved.

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2. LIGHTHILL, M. J. On Sound Generated Aerodynamically: II Turbulence as a Source of Sound. *Proceedings of the Royal Society*, Vol. 222, 1954, pp. 1-32.

# The Excitation of Structural Vibrations by Noise

by

R. E. FRANKLIN

(*Engineering Laboratory, University of Southampton*)

A CONSIDERABLE research effort is now directed at the problem of vibrations excited in aircraft structures by airborne sound from the power plants. Both jet and propeller aircraft are involved, although perhaps for different reasons. With jet aircraft the problem is to make the structure strong enough to withstand the vibrations and the accompanying stress fluctuations; with propeller aircraft the problem is usually to prevent the transmission of sound through the structure into the passenger cabin.

When dealing with either of these two problems, it is important to realise from the start that they are actually only two different aspects of a single problem and, moreover, a problem which has already received considerable attention in the field of acoustics, namely the transmission of sound through walls. Here the problem is looked at in a qualitative manner in order to clarify the physical mechanisms involved.

In acoustics, when considering the transmission of sound through a wall the simple case which is usually

dealt with is that of an infinite, flexurally rigid, elastically-supported, thin panel at one side of which plane waves are arriving at normal incidence. Under the combined effect of the incident, reflected and transmitted waves, the panel vibrates like a piston and the equation of motion is easily set up and solved. The equation is usually solved for the reduction factor, *i.e.* the ratio of the intensities of the incident and transmitted waves, or the transmission loss, which is the same quantity expressed in decibels. The transmission loss is found to vary as shown in Fig. 1.

The transmission loss for finite panels is found to behave somewhat differently, particularly at frequencies above that corresponding to the first resonance. There are two main reasons for this.

The first is a straightforward case of resonance. The panel has an infinite number of modes of vibration and as the frequency of the incident wave approaches the frequency associated with each of the modes of vibration, resonance can occur and the transmission loss will fall to an extent which depends upon the damping in the mode.

The second effect is one which really has no connection with resonance, although it is frequently confused with it. An infinite plate can support free-running flexural waves, just as air can. However, unlike air, in which the velocity of a wave is practically independent of the frequency, a plate is a dispersive medium, by which is meant that the velocity of a flexural wave depends upon its frequency. If in the case under consideration the plane sound waves are not at normal incidence, *i.e* the wavefronts make an angle with the panel surface, a trace-wave will run along the panel at a speed depending upon the incidence. The velocity of the trace-wave is in fact $(c/\sin\theta)$ and so can vary from the normal speed of sound, $c$, when $\theta = 90°$ (grazing incidence), to infinity, when $\theta = 0°$ (normal incidence). This trace-wave tends to force a running wave into the panel and it may be possible to find an angle of incidence at which the velocity of the trace-wave equals that of free-running waves in the panel at the frequency of the sound. This phenomenon is known as coincidence. Bearing in mind the fact that the slowest speed of the trace-wave for all frequencies is equal to the velocity of sound, it is clear that there is a cut-off frequency below which coincidence cannot occur. For an aluminium sheet $\frac{1}{8}$ in. thick this cut-off frequency is 3680 c.p.s. At frequencies greater than this, coincidence can occur and since at coincidence the panel appears almost transparent to the sound (if the damping is small) the transmission loss becomes very small.

As stated earlier, the problem of the failure by fatigue of components in a noise field is precisely the same as that already discussed. The only difference is that attention is focused on a different aspect of the problem, namely the amplitude of vibration of the panel and the effects of this vibration in producing stresses in the panel and its supports. The factors which influence the intensity of the transmitted sound must be the factors which influence the amplitude of vibration of the panel, for it is only by vibrating that the panel can transmit sound.

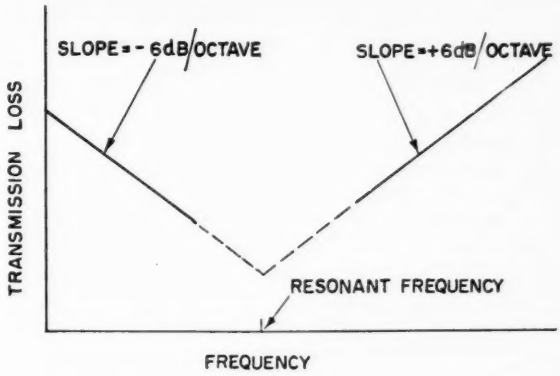


FIGURE 1.

Another approach to this problem is to consider the generalised force on a panel. Suppose a panel which can only vibrate like a piston is mounted in a large baffle. Then if sound waves fall upon it at oblique incidence it is clear that when the trace-wavelength seen by the panel is equal to the panel length, there will be no generalised force, for the pressures in the two half-waves cancel. This is true for all situations in which the panel length is equal to an even number of half trace-wavelengths. The generalised force is a maximum when the panel length equals an odd number of half trace-wavelengths but rapidly decreases as the wave-number increases. Thus, besides acting as a frequency filter by virtue of its mass and stiffness, the panel also acts as a wave-number filter.

Suppose now that the panel is not flexurally rigid but can break up into its modes. If the sound waves falling on it are at normal incidence then an argument similar to that in the previous paragraph suggests that the panel will respond mainly in its first mode. The reason for this is that when the wave-fronts are parallel, or nearly parallel, to the panel surface, the phase of the pressure is everywhere the same and so work is only done on those modes which have an odd number of half-waves. Another way of saying that the pressure is in phase over the surface is to say that the space correlation coefficient of the pressures is unity for separations of the order of the panel size. The correlation between the pressures at points 1 and 2 is $\overline{p_1 \cdot p_2}$ where the bar indicates a time-average, and this measures the " power " between the two pressures just as the time-average of the product of voltage and current in an a.c. circuit measures electrical power. When $\overline{p_1 \cdot p_2}$ is normalised the resulting space correlation coefficient is in many ways similar to the power factor $\cos\phi$ in the electrical circuit.

Thus in cases where the space correlation coefficient of the pressures is nearly unity for all separations on the panel, the wave-number filter effect is negligible and the panel will vibrate mainly in its first mode. Quite simple calculations will then give a good estimate of panel amplitudes (*see* Ref. 1).

Although panel sizes on aircraft are likely to fulfil this condition, the fact that a panel will communicate

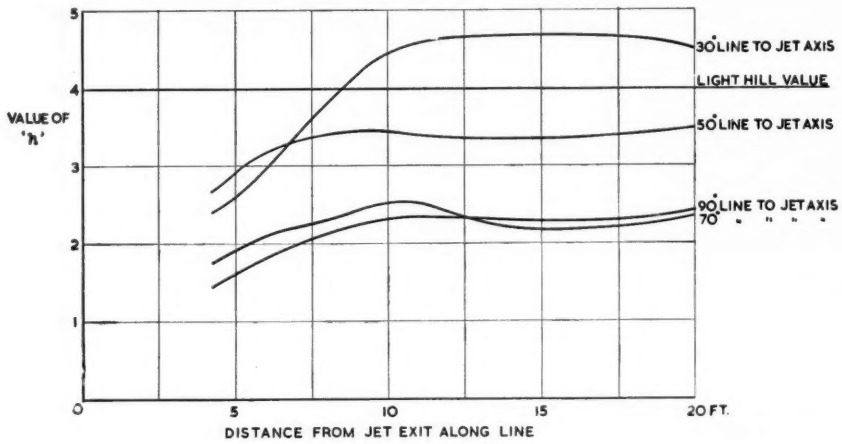


FIGURE 8. Acoustic pressure law index for velocities 400-1850 ft. per sec. Variation of "$n$" along lines at angles to the jet axis.

One can, however, draw certain general conclusions. The first is that since the excitation spectra are continuous there is not much hope of improving matters by detuning the structure to avoid resonance. It would therefore seem that stiffening the structure on broad strength considerations would be a more profitable approach. This would also raise its natural frequencies and, since the excitation spectra appear to be less intense at the higher frequencies, this should be beneficial. Structure damping is also probably more effective at higher frequencies.

This argument implies that the ratio of skin thickness to stringer and frame spacing should be as high as is compatible with other design considerations. There is already some evidence to show that this is so and, in particular the honeycomb sandwich type of construction, which represents an extreme example of this rule, appears to be good.

The other general conclusion that may be drawn is that since natural frequencies of the structure appear to be involved and the stresses are low by normal fatigue standards, considerable improvement may be gained by the introduction of even small amounts of damping. Here again a honeycomb sandwich type of construction would appear to be an obvious choice. Finally it should be mentioned that in this, as in all fatigue problems, careful avoidance of stress raisers in design is an obvious precaution.

## Acknowledgment

The author is indebted to the Chief Scientist, Ministry of Supply, for permission to publish this paper. The illustrations are Crown Copyright reserved.

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# The Excitation of Structural Vibrations by Noise

by

R. E. FRANKLIN

(*Engineering Laboratory, University of Southampton*)

A CONSIDERABLE research effort is now directed at the problem of vibrations excited in aircraft structures by airborne sound from the power plants. Both jet and propeller aircraft are involved, although perhaps for different reasons. With jet aircraft the problem is to make the structure strong enough to withstand the vibrations and the accompanying stress fluctuations; with propeller aircraft the problem is usually to prevent the transmission of sound through the structure into the passenger cabin.

When dealing with either of these two problems, it is important to realise from the start that they are actually only two different aspects of a single problem and, moreover, a problem which has already received considerable attention in the field of acoustics, namely the transmission of sound through walls. Here the problem is looked at in a qualitative manner in order to clarify the physical mechanisms involved.

In acoustics, when considering the transmission of sound through a wall the simple case which is usually

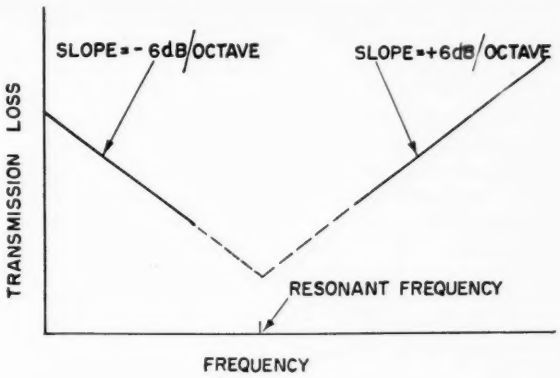
dealt with is that of an infinite, flexurally rigid, elastically-supported, thin panel at one side of which plane waves are arriving at normal incidence. Under the combined effect of the incident, reflected and transmitted waves, the panel vibrates like a piston and the equation of motion is easily set up and solved. The equation is usually solved for the reduction factor, *i.e.* the ratio of the intensities of the incident and transmitted waves, or the transmission loss, which is the same quantity expressed in decibels. The transmission loss is found to vary as shown in Fig. 1.

The transmission loss for finite panels is found to behave somewhat differently, particularly at frequencies above that corresponding to the first resonance. There are two main reasons for this.

The first is a straightforward case of resonance. The panel has an infinite number of modes of vibration and as the frequency of the incident wave approaches the frequency associated with each of the modes of vibration, resonance can occur and the transmission loss will fall to an extent which depends upon the damping in the mode.

The second effect is one which really has no connection with resonance, although it is frequently confused with it. An infinite plate can support free-running flexural waves, just as air can. However, unlike air, in which the velocity of a wave is practically independent of the frequency, a plate is a dispersive medium, by which is meant that the velocity of a flexural wave depends upon its frequency. If in the case under consideration the plane sound waves are not at normal incidence, *i.e* the wavefronts make an angle with the panel surface, a trace-wave will run along the panel at a speed depending upon the incidence. The velocity of the trace-wave is in fact $(c/\sin\theta)$ and so can vary from the normal speed of sound, $c$, when $\theta = 90°$ (grazing incidence), to infinity, when $\theta = 0°$ (normal incidence). This trace-wave tends to force a running wave into the panel and it may be possible to find an angle of incidence at which the velocity of the trace-wave equals that of free-running waves in the panel at the frequency of the sound. This phenomenon is known as coincidence. Bearing in mind the fact that the slowest speed of the trace-wave for all frequencies is equal to the velocity of sound, it is clear that there is a cut-off frequency below which coincidence cannot occur. For an aluminium sheet $\frac{1}{8}$ in. thick this cut-off frequency is 3680 c.p.s. At frequencies greater than this, coincidence can occur and since at coincidence the panel appears almost transparent to the sound (if the damping is small) the transmission loss becomes very small.

As stated earlier, the problem of the failure by fatigue of components in a noise field is precisely the same as that already discussed. The only difference is that attention is focused on a different aspect of the problem, namely the amplitude of vibration of the panel and the effects of this vibration in producing stresses in the panel and its supports. The factors which influence the intensity of the transmitted sound must be the factors which influence the amplitude of vibration of the panel, for it is only by vibrating that the panel can transmit sound.

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Thus in cases where the space correlation coefficient of the pressures is nearly unity for all separations on the panel, the wave-number filter effect is negligible and the panel will vibrate mainly in its first mode. Quite simple calculations will then give a good estimate of panel amplitudes (*see* Ref. 1).

Although panel sizes on aircraft are likely to fulfil this condition, the fact that a panel will communicate

its motion to adjacent panels will mean that the structure will be set in motion over an area comparable with, if not greater than, the correlation area.

When the panel is not flexurally rigid and, further, the sound waves arrive at an oblique incidence, it seems likely that an effect similar to coincidence will occur. This is in fact the case. Thus on considering the generalised force in a given mode it is clear that it will be a maximum when the trace-wave matches into the mode shape. As in the case of the rigid panel, the panel acts as a wave-number filter, the filter now being centred on the wave-number corresponding to the length of a panel wave. As the mode contains more and more half-waves, the filter becomes highly selective.[2]

The condition that makes the wave-number filter characteristic appear is that trace-wavelengths comparable to, and smaller than, the panel size occur. This means that the phase of the pressure at any instant varies rapidly over the panel. In other words, the correlation length is comparable to, or smaller than, the panel dimensions. This is the situation referred to above when a structure vibrates as a whole rather than panel by panel. When the sound falling on the panel is noise, then many modes may be excited and, although they are relatively straightforward, calculations become complicated, for each mode acts both as a frequency and a wave-number filter.

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# The Effect of Structural Damping upon the Stresses due to Jet Efflux

by

D. J. MEAD, D.C.Ae., A.F.R.Ae.S.

(*Engineering Laboratory, University of Southampton*)

THE REDUCTION of the vibration amplitudes of a system subjected to external exciting forces can often be achieved by a suitable alteration in the mass or stiffness of the system. The natural frequencies of the system are thereby changed and are no longer in the neighbourhood of the peak harmonic components of the exciting force. This procedure can be shown to have little effect on the problem of jet efflux excitation (unless a really radical change of stiffness is made, such as could only be obtained by a complete change in the type of construction). This is due to the jet efflux pressure field having a fairly flat pressure spectrum and therefore containing harmonic components of all frequencies (over its range of flatness) which are more or less equal in magnitude. However, despite this flatness the spectrum of the generalised force exciting a particular mode has a large peak at the frequency where the sound wave of that frequency has the same wavelength as the structural mode (the coincidence effect).

The structural modes being considered here are those in which distortion of the cross section occurs, this distortion varying along the length of the structure. On a typical stiffened fuselage it can be shown that there are several modes of this type which have natural frequencies in the neighbourhood of the frequency of the peak in their respective force spectra. These modes can be expected to play the dominant part in the vibration excited by the jet efflux[1]. A small change of stiffness or mass might separate these frequencies for one mode and thereby reduce the amplitude in that mode, but it will probably draw them closer for another mode, so that the total amplitude may be almost unchanged.

Since the vibration in each mode occurs at, or near, the natural frequency, the damping will be the most important factor in determining the amplitude for a given excitation field. An increase of damping in each mode will cause a certain decrease of amplitude in each mode, and hence in the total response.

The damping of a component such as a rear fuselage derives from three main sources. Firstly, the structural damping, which arises from structural hysteresis. In an orthodox structure, this has been shown to originate mainly at the numerous riveted and bolted joints. Secondly, the acoustic damping, arising from sound energy being radiated away by the vibrating surfaces. Thirdly, the damping arising from friction introduced by sound-proofing, internal furnishings, stowed equipment, and so on. Of these three sources an efficient increase

is conceivable only for the structural damping. Whether or not this is worth-while depends upon the magnitude of the possible increase, and upon the relative magnitudes of the three sources—this latter as yet being unknown. The following remarks are, therefore, tentative suggestions pending the arrival of this knowledge.

The mechanism whereby a riveted joint can give rise to damping forces, and energy dissipation may be envisaged by considering two plates riveted together as a single butt joint. A well-formed rivet completely filling the hole will exert an internal pressure within the hole. This, together with the effect of forming the rivet head, causes a normal pressure to exist between the plates, and a corresponding frictional force will resist relative tangential displacements of the plates. When the joint is loaded harmonically, this frictional force must first be overcome before the rivet takes appreciable load. Thereafter the rivet load causes rivet deflection and relative slipping of the plates against the dynamic friction. Work must be done against this, energy is dissipated, and a system of damping forces exist. Preliminary work on single joints indicates that the damping force is non-linear, and is not proportional to the amplitude, as is often assumed for simplicity. In vibrating beams such as a stringer-skin combination, where the two components are riveted together along the length, the shear load per rivet varies along the length of the beam, and the extent of the beam over which rivet slip occurs will vary with the displacement of the beam. The non-linearity of the overall damping will then be more pronounced.

To increase the structural damping, greater rivet slip or dynamic friction would appear to be required, but this has the obvious disadvantage of reduced stiffness and increased danger of fretting and fatigue. It has been shown[2] that an increase of several times may be obtained by the insertion of a thin layer of certain compounds or materials between the joint plates. The former frictional shear stresses now have to pass through the insert which, having either a high viscosity or low yield stress, readily absorbs energy. The amount of slip between the plates is probably increased, and the effect of this in bending the rivets must be investigated, but the danger of fretting is altogether removed since there is now no metal-to-metal rubbing.

The structural damping of a component such as a fuselage takes place at the joints between skin and stringers, skin and frames, and at the longitudinal and circumferential skin-to-skin joints. The overall damping factors in each mode of vibration will be different, since in different modes a given joint has different loads and therefore contributes a different amount to the total damping. The total damping from the whole structure will therefore vary from mode to mode. If experience shows that in the main modes of vibration excited by the jet efflux certain joints are always highly loaded, while others are lightly loaded, then damping inserts should be introduced only at the highly loaded joints for the greatest efficiency. However, it seems more probable that each joint will be highly loaded in one or another of the excited modes, indicating that inserts will be required at all, or most, of the joints.

A programme of work has been started at the University of Southampton to investigate the relative magnitudes of the sources of damping and to determine the increase in damping that may be obtained by inserts, damping tape and other methods. A comparison is to be made between the damping of riveted and Reduxed components, using specimen pieces vibrating as simple beams. In experiments of this nature, where frequencies of up to 500 c.p.s. are to be encountered, the acoustic damping must be separated from the structural. The experiments will therefore be performed in a pressure chamber, in which the air density, and hence the acoustic damping, can be varied, enabling the acoustic effects to be separated from the structural. In a riveted stringer-skin combination vibrating as a beam, a thorough understanding of the damping can only be obtained if the variation of energy dissipation along the beam is known. A method is therefore being developed to measure this.

Further work is to be conducted to study the damping due to a riveted frame-skin combination, in which skin joints will be added. Finally, a test is envisaged on a model fuselage having frames, stringers and joints similar to those already tested. Having obtained a thorough understanding of its system of damping, it will be possible to predict the most efficient manner in which the damping may be increased.

It is recognised that certain problems attend the use of joint inserts. The material used must maintain its damping properties over a wide range of temperature, since it must be used in the vicinity of a hot jet. The insert must not permit sufficient slip to cause appreciable rivet bending stresses. The fatigue life of riveted joints with inserts must therefore be investigated.

It is believed that the structural damping may be increased by a factor of ten or more by the use of inserts. If this results in an increase of five times in the total damping, then the displacement and stress amplitudes will be reduced by 80 per cent. This could result in a satisfactory prolonging of the fatigue life of structures which formerly encountered fatigue failures after a relatively long period. In the case of structures which have failed after a short exposure to the jet efflux, a reduction of 80 per cent in the stresses will probably not extend the fatigue life to an acceptable extent. Much more radical structural changes will then be required than attempting to increase the damping.

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# Stresses Produced in Aircraft Structures by Jet Efflux

by

B. L. CLARKSON, B.Sc., Ph.D., Grad.R.Ae.S.

*(The de Havilland Aircraft Co. Ltd.)*

THE SOUND PRESSURES, associated with a jet efflux, set up stresses in an aircraft structure which are essentially those occurring in the resonant condition of the structure. These sound pressures contain components in a wide range of frequencies and the resultant stresses in the structure have low magnitude by normal structural standards but, because of the high frequency, they are very important from the fatigue standpoint. A rigorous theoretical approach is being developed at Southampton University which, although extremely difficult to apply to actual aircraft structures, emphasises the factors which must be considered. However, for immediate practical use it is suggested that an approximation can be made to render the problem tractable. It is considered that in an actual aircraft the effects are primarily local and on this assumption an approximation is developed and compared with test results. Reference is made specifically to the de Havilland Comet aircraft.

Figure 1 shows the familiar layout of the Comet. The efflux from the jet engines passes close to the fuselage and tailplane and consequently gives rise to high frequency, low magnitude, stresses in these members. The highest sound pressures occur on the fuselage at a point some 4 ft. forward of the pressure dome, a point which is about 15 ft. from the jet exit nozzle. A ground running test was made on a Comet 1 aircraft and strain gauges were attached to stringers running along the fuselage, as shown at positions 1 to 6. These gauges were placed at mid-frame positions and record stringer bending strains. Gauges were also placed at other positions but reference is made particularly to these stringer strain gauges.

The mean bay of this stringer is about 20 ft. (13 nozzle diameters) from the jet exit nozzle and is receiving sound pressures having components in a wide frequency range. The high frequency noise seems to originate from close to the nozzle, point *A*; the mid-frequency noise from a point such as *B* and, the lower frequency from a point some distance downstream such as point *C*. Thus, points on the fuselage side receive components varying randomly in phase and also having different angles of incidence. Reflection from the runway and adjacent structure also tends to complicate the position. The result of this appears to be that there is random phase relationship between pressure components at a given frequency at different positions on the fuselage.

This lack of phase relationship suggests that the predominant form of vibration is that of local vibrations of panels and stringers, rather than vibration of the whole structure as a stiffened cylinder. The structure is composed of an outer skin with stringers Reduxed to it at about 6 in. pitch and the whole is attached to circular frames. Local vibrations are now possible with stringers vibrating between frame fixing points. Fig. 2 shows an extract from a recording of strains at points 1 to 6 on the fuselage stringer and it is seen that there is little phase relationship between gauges, with the exception of gauges 1 and 2. This confirms the view that for points in the near field an approximation can be made by considering only local vibrations of panels and stringers, and so on.

On the tailplane the position is slightly modified. During ground running, vibration of the whole tailplane at about 6 c.p.s. can be observed but on examining strain recordings, it is seen that on top of this low frequency vibration is superimposed a much higher frequency vibration coinciding with local frequencies of stringers and skin panels. The structure is identical top and bottom, but damage has been confined chiefly to the bottom attachments, which again points to local effects.

As the force applied to the structure contains components in a wide frequency range, resonance of the structure occurs. The local components, such as stringers, which are vibrating are lightly damped and therefore respond primarily to forces applied at their resonant frequencies. Thus only pressures applied at frequencies in the region of the natural frequency have any appreciable effect on the response. Each natural mode of vibration can be considered separately and then the final response is approximately equal to the sum of the effects occurring at each resonant frequency.

For the single degree of freedom case (*e.g.* panel vibrating in its first natural mode at frequency $\omega_n$ and with the proportion of critical damping equal to $\delta$) the

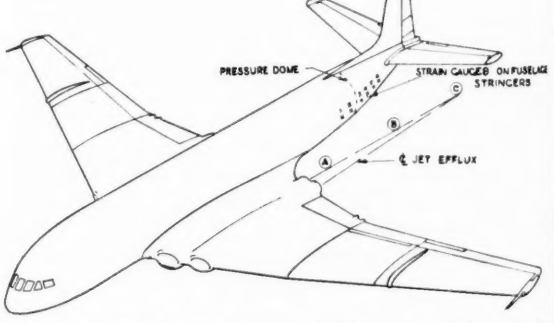


FIGURE 1. de Havilland Comet. Position of jet efflux relative to aircraft structure.

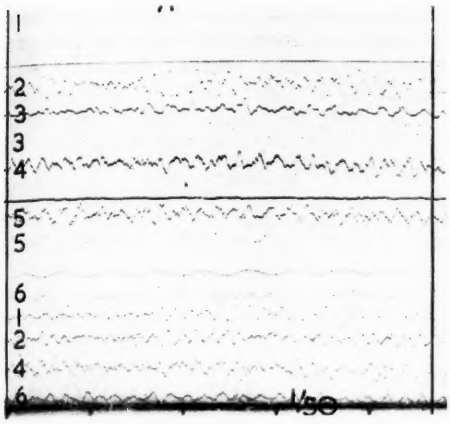


FIGURE 2 (*left*). Typical strain records.

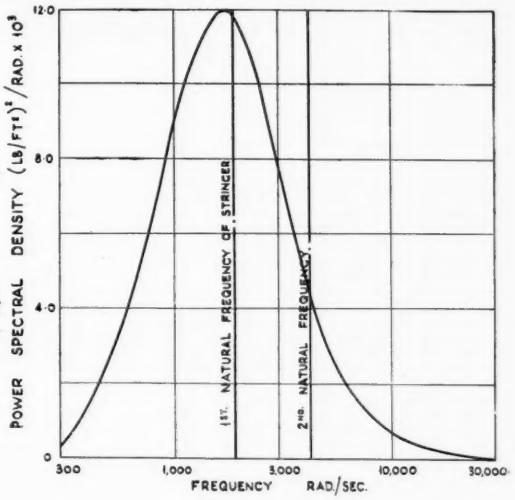


FIGURE 3 (*right*). Power spectrum of pressures on fuselage side.

panel will only respond to pressure components having frequencies in the region $\omega_0 \pm \delta\omega_0$. This band width contains several frequencies and each makes a contribution to the final response. Miles [1] has shown that if these components have random phase relationship with each other, then the response will take the form of a wave having the mean frequency $\omega_0$ and an amplitude envelope varying in a random manner. The mean square value of the stress envelope is given approximately by:—

$$\overline{S^2} = \frac{\pi}{4\delta}\,\omega_0\, p(\omega_0)\, S_0^2$$

where $\omega_0$ resonant frequency

$\delta$ proportion of critical damping (assumed small)

$p(\omega_0)$ power spectral density of pressure at frequency $\omega_0$

$S_0$ static stress per unit input pressure.

Turning now to the particular case of the stringer on the side of the Comet fuselage, the applied sound pressures have a power spectrum as shown in Fig. 3. This spectrum has been derived from an octave band analysis of sound measurements. The spectrum shows that for this point on the aircraft the peak pressure is applied at 1,650 rads/sec. (263 c.p.s.). The first natural frequency of the stringer is at 300 c.p.s. and the second at 670 c.p.s., both of these being shown on Fig. 3. It is seen that in this case the first mode has a frequency almost coinciding with the peak applied pressure, whereas the pressure at the second frequency is considerably reduced.

Consider now bay No. 2 of the stringer, where the power spectrum of the pressures is as shown in Fig. 3. The following simplifying assumptions are made:—

1. Vibrations set up at this point in the near field are essentially those of local vibrations of the stringer panel. The justification of this has already been discussed.
2. The power spectrum of applied pressures remains constant along the length of the bay. The bay is 20 in. long and therefore there is some variation along it, but this is not considered to be an appreciable effect.
3. At a given point the pressure components bear random phase relationship with each other; but a component at a given frequency is directly in phase all the way along the bay. The first part of this assumption is reasonable but the second needs more justification. The stresses in the stringer are most sensitive to pressures applied in the central region (for the first two modes) and therefore, if there is a phase difference towards the ends this will not appreciably affect the result.

With these assumptions it is now possible to consider each mode of vibration of the stringer and calculate the envelope mean square stress by the relationship quoted above.

The response or mean square value of the stress envelope varies inversely as the proportion of critical damping and directly as the frequency and power spectral density at that frequency. The value to be used for the proportion of critical damping present is difficult to estimate but, as the root mean square stress varies inversely as the square root of the damping, the error from this source should not be large. Then, using an approximate value for the damping the mean square value of the stress envelope is obtained. The same procedure is also adopted for the second mode, and any higher modes have negligible pressures associated with them. The mean square value of the total response is approximately equal to the sum of the mean squares of the two components. Estimates obtained in this way give r.m.s. stresses of the same order as those measured on the aircraft and form the starting point for fatigue life estimates.

The actual trace should now be made up of two components, one at a frequency of 300 c.p.s. with a

randomly varying envelope and the other at 670 c.p.s., also with a randomly varying envelope. This effect can be seen clearly in Fig. 2, gauge 2.

In conclusion it is suggested that the stresses in any aircraft structure situated in the near field region of a jet efflux are primarily ones associated with local vibrations of skin panels and stringers. By assuming no spatial phase, or pressure, change in each frequency component over this small area and also, a value for the damping, a reasonable approximation to the r.m.s. value of the stress envelope is obtained.

## Acknowledgment

The author wishes to thank the de Havilland Aircraft Co. Ltd., for their encouragement and permission to discuss work done on their behalf.

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# Experimental Study of the Effects of Jet Noise on an Aircraft Structure

by

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(*Vickers-Armstrongs (Aircraft) Ltd., Supermarine Works*)

REPORTS OF NOISE effects on the rear fuselage structure of large British aircraft indicated that one might expect noise damage in this region on the Vickers Supermarine Type 544 aircraft. It will be seen from Fig. 1 that the jet efflux from each engine passes close to the fuselage side and under the tailplane. The fuselage structure proper is, however, protected from the heat and noise effects at the jet efflux by a fairing which is insulated at all attachments. This fairing, by virtue of its shape, is called the "pen nib."

It was decided to begin a noise investigation programme before prototype flying began in order that any structural modifications which might prove necessary could be made without affecting aircraft production. Two development aircraft, similar in configuration to Type 544, had been flying for some time and had sustained slight damage to their pen nib fairings, hitherto attributed to heat effects.

One of these aircraft became available for noise research and it was decided to study the resonant frequencies of several rear fuselage and tailplane panels and a machined fitting.

The structure was excited by a loudspeaker and the response of each structural item was recorded by a strain gauge mounted at the estimated position of maximum bending stress for the fundamental mode.

All the items investigated showed strong fundamental resonances in the range 100 to 600 c.p.s. and over-tones were detected up to 5,000 c.p.s.

A portion of a typical resonance curve for a fuselage skin panel is shown in Fig. 2; the full line shows the amplitudes obtained with the bare panel and the dotted lines show the effect of adding layers of sound damping tape.

The sound damping tape was supplied in a 6 in. wide roll and consists of a strip of cotton cloth and a layer of aluminium foil laminated together. The cotton cloth is coated on both surfaces with a pressure-sensitive

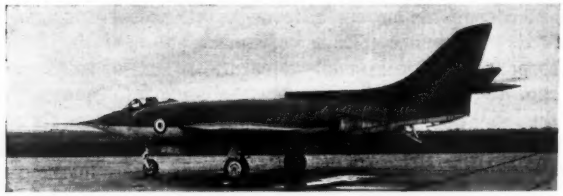

FIGURE 1. Vickers Supermarine Type 544 aircraft.

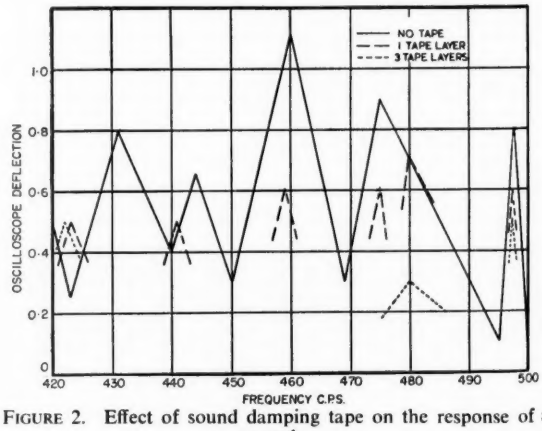


FIGURE 2. Effect of sound damping tape on the response of a panel.

substance to stick it to the foil and structure respectively.

To provide endurance data, it was decided to build a full-scale rear fuselage specimen which would be subjected to the jet efflux of a Rolls-Royce Avon engine. This specimen consisted initially of a half fuselage incorporating the region from the jet efflux to the end of the pen nib structure. It was later extended to include the tailplane.

After 40 minutes' engine running, failure of the pen nib fairing occurred and a piece of the fairing was torn away. This fairing was later replaced by a much heavier steel panel and with one or two minor modifications in this region the prototype aircraft was cleared for initial flights. Subsequent test work enabled the gauge of the heavy steel pen nib to be substantially reduced, the final weight penalty over the original design being comparatively small.

The engine was run for half-hour periods at a time, each period consisting of 28 minutes at maximum cruising r.p.m. and two minutes at take-off r.p.m. A total of 20 hours was completed in this way and the resulting noise damage was compared with that sustained by the aircraft. It was found that one hour of test rig running was equivalent to about 10 flying hours on the aircraft.

Damage sustained during these runs was confined mainly to secondary structure and fairings, so that the safety of the aircraft was not materially involved, but it was considered that any failure which would decrease serviceability, or increase maintenance work on a carrier-based aircraft, should be obviated if possible.

Damage usually began at countersunk skin attachments, which would first loosen and later lose their heads, the rivets finally falling out altogether. Countersunk holes were also a source of weakness and became connected with cracks. These troubles were overcome by replacing countersunk rivets by mushroom head, or snaphead, rivets wherever aerodynamically possible, or by increasing the thickness of material locally and by cut-countersinking.

As the test proceeded, certain internal stiffeners developed cracks at discontinuities and changes of section. This damage was typical of fatigue failure in general, the material bounding the cracks being highly polished. There were also joints showing severe fretting where they had worked after rivets had loosened.

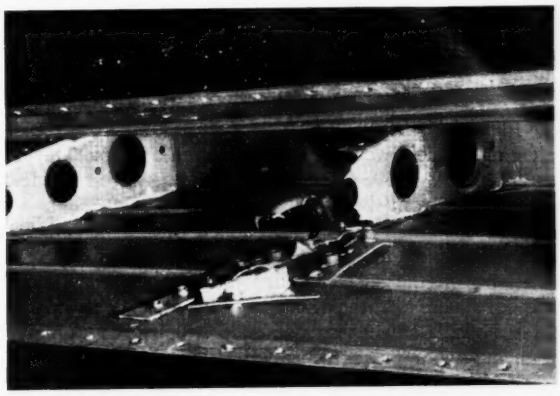

FIGURE 3. Cracking of the light trailing ribs in the tailplane.

Cracking of the light trailing ribs in the tailplane was most severe and the items were reduced to pieces (Fig. 3).

This trailing structure was modified, for a small weight penalty, and the revised construction has already successfully withstood the equivalent of 150 flying hours. The modification involved fitting light mild steel ribs and the addition of chordwise integral stiffeners to strengthen the skin riveting.

A number of noise and stress measurements were made during these endurance tests in order to relate the damage observed to the noise producing it. Noise measurements at various positions in the near field were made over a wide range of engine r.p.m., the total noise being plotted against log of jet velocity for each position. It was found that a large increase in noise propagation occurred above choking, represented by a sharp kink in the graphs, which were otherwise linear.

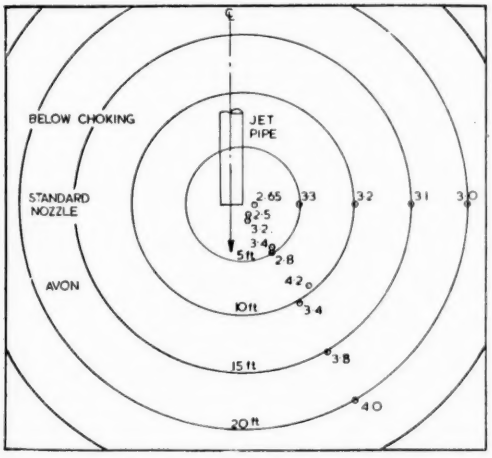


FIGURE 4. Near field values of $N$ in the expression noise $\propto V_j^N$.

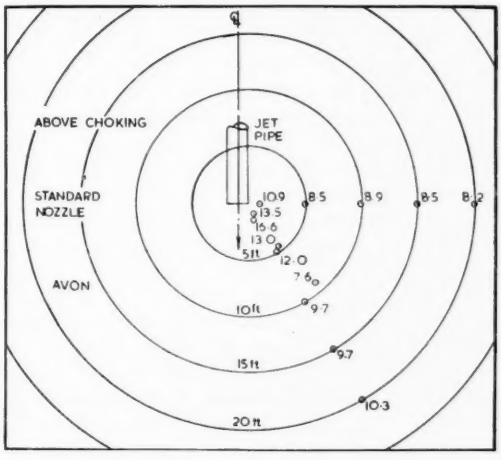


FIGURE 5. Near field values of $N$ in the expression noise $\propto V_j^N$.

Figure 4 shows the slope of the total noise graph obtained at each position, below choking. The figures indicate the value of $N$ in the expression noise intensity $\propto V_j^N$ where $V_j$ is the jet shear velocity.

Figure 5 shows the values of $N$ obtained above choking, which were very much greater; noise levels up to 162 dB above 0·0002 dyne/sq. cm. were recorded at one foot from the centre of the jet nozzle.

The specimen was strain gauged during the endurance runs and alternating stress in various panels was analysed on the spectrum analyser. The stress levels recorded were low, the majority being below $\pm 1$ ton/in.$^2$ Discrete isolated peak stresses at least 25 per cent greater than the average occurred about once in three seconds.

Endurance testing carried out on this test rig has indicated certain broad lines on which structures could be developed in order to withstand jet noise.

During part of the endurance programme two small panels were mounted below the fuselage so as to be subjected equally to the noise effects. The panels were of the same total weight for unit area, but one was of sandwich construction and the other was braced with a cross of conventional Z-stringers. Rivet failures occurred on the stringer panel after a few hours running, one short piece of stringer being allowed to fall off entirely. The sandwich panel was quite intact.

The method used to combat noise damage on the pen nib fairing was to remove all stiffening and to support the panel around the edges only. There were thus no rivet holes within the fairing boundary and no concentrated masses to create inertia loads normal to the panels.

Impressions gained through doing this work can be summarised briefly as follows: —

The jet engine provides a "white" spectrum of intense noise over a very large bandwidth; it is not, therefore, feasible to "detune" the structure by stiffening, which merely shifts the resonance from one part of the spectrum to another.

Noise damage is a fatigue phenomenon and structures which will be subjected to jet noise should be studied carefully in the design stage in order to avoid discontinuities, changes of section and attachment holes as much as possible. Furthermore, at our present state of knowledge, clearance of the aircraft structure to give a satisfactory life must rest on extensive and expensive full-scale testing.

Engines now contemplated for future generations of aircraft will undoubtedly produce considerably greater noise levels than those experienced at present. It may therefore prove essential that such aircraft have no structure in the hemisphere aft of the jet efflux.

ACKNOWLEDGMENT

In conclusion, the author wishes to thank Vickers-Armstrongs (Aircraft) Ltd. for permission to publish the data given in this Discussion.

# Summary of the Discussion

by

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THE TIME-TABLE for the Symposium was arranged so that the papers were read first and a general discussion followed. A large number of delegates spoke on a wide range of topics and thus it was not convenient to report the discussion verbatim. The following notes, therefore, attempt to summarise some of the main topics covered and the opinions expressed.

In the course of the discussion, further details were given of the construction and calibration of the capacitance microphone developed at the R.A.E. for the measurement of jet noise. The use of a frequency analyser with the equipment enabled noise spectra to be determined. Thus with a knowledge of the noise spectrum, fatigue tests could be made at the appropriate stress levels in order to determine the life of components. The alternatives of using recorded or actual jet engine noise for testing structures were also considered.

As yet there were comparatively few fatigue test data at stresses as low as those produced by jet noise. This was partly due to the relatively high endurance (often of the order of $10^{11}$ cycles) at these low stress levels, and the consequent length of time that the tests would take. Methods were mentioned in which small specimens could be vibrated by electrical means in order to give high frequency fatigue loading. The use of these high frequencies led to the question of the effect of speed of testing on the results, and it was stated that some tests have shown that over a range of frequency from 100 to 10,000 cycles per second, the safe fatigue range was somewhat higher at the higher frequencies.

In general, it was difficult to produce jet efflux frequencies in alternating tension machines, and rotating-bending or alternating-bending methods had to be used. This might lead to difficulties in relating the results to the endurance of a component subjected to a tensile load.

For components subjected to jet noise, the information that the designer required was the fatigue life, and thus a working theory giving this information and

taking into account all the significant variables would be most useful. Even should suitable fatigue data become available, however, the determination of stress distribution in the structure due to jet noise was complicated by the large number of natural modes of vibration and by the effects of stress concentration at rivet holes and so on. In many cases, therefore, it would be useful to have a simple theoretical or empirical approach which would indicate whether the structure was of good design from the jet noise standpoint. Such indications could always be checked by tests subjecting components to the noise of actual jet engines or to suitable recordings, but it was particularly important that large or complex components should be of good design in the first place in order to avoid costly modifications.

A more general point mentioned was that jet noise, boundary layer instabilities, and buffeting might all bring about similar effects on an aircraft structure since each may produce high frequency pressure changes.

For parts of the structure of an aircraft subjected to jet noise effects, consideration must be given to the choice of material. This choice would be governed by points such as the fatigue characteristics of the material, the extent of internal damping in the material and, if the component were in a hot region close to the jet pipe, the thermal properties of the material. In this connection the relative merits of steels and titanium alloys were discussed.

The importance of structural damping and stiffening was emphasised in the discussion. Stiffening a structure generally produced higher modes of vibration and thus the increased damping associated with these modes lessened the induced stresses. It was noted that riveted joints might produce a large proportion of the damping in many structures and that this could probably be increased by a thin sheet of a suitable plastic material placed between the plates at the joint. The use of a special damping tape, stuck to the inside surface of panels, was also mentioned.

A disadvantage of panels with riveted stiffeners was that failure could occur at the riveted connections. Failure at riveted connections was sometimes noted in the regions very close to the nozzle of an engine, *e.g.* in "pen-nib" fairings, where heating effects aggravated the situation. In such regions it had been found best to avoid stress concentrations and to use an unstiffened panel, usually of steel.

Panels of honeycomb construction had a number of advantages, such as virtually eliminating panel vibration, the comparative absence of riveted connections and they also had good damping properties. The choice between the honeycomb construction and large unstiffened panels could depend on whether or not the component in question was taking any appreciable load.

There was a further suggestion that unstiffened panels might be constrained to vibrate in higher modes, with only a small weight penalty, by using wires to attach points on the panel to more rigid parts of the structure.

Work was being continued by engine manufacturers and others on the reduction of jet noise, although much of this was aimed at reducing jet noise on the ground. To a large extent the reduction of jet noise close to the engine was incompatible with the demands for increased power and decreased fuel consumption.

Placing the engine at the rear of the aircraft was an obvious help, although this was not always practicable. Sometimes an appreciable amount of noise also occurred in front of the engine, but this generally emanated from the compressors and was of a higher frequency range.

It was important to note that the greatest damage due to jet efflux effects would occur when the relative velocity between the jet efflux and the surrounding air was a maximum, that is at full engine thrust when the aircraft was just beginning its take-off run. As the forward velocity of the aircraft increased, the shear velocity at the edge of jet decreased and thus the noise level decreased. This has led to a variation in take-off procedure which has been used with at least one aircraft. For this case the aircraft started its take-off run at less than maximum thrust, and the thrust was increased as the forward velocity increased.

A further suggestion was that if trouble occurred at the trailing edges of the wing or control surfaces, then a light plastic or plastic foam could be used as a filler in order to reduce vibration. It was thought, however, that in some cases there would be difficulty owing to effects of temperature on plastics.

# Effects of Inlet Boundary Layer on Pressure Recovery, Energy Conversion and Losses in Conical Diffusers

by

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SUMMARY:— A study has been made of the effect of inlet conditions on the performance of conical diffusers with 4:1 area ratio and 5 and 10 degrees total angle of expansion. The conditions at entry were varied by using different approach lengths of diffuser inlet diameter, and by means of projecting annular screens of woven wire cloth. With this new technique it was possible to vary the velocity distribution substantially within moderate settling lengths, and to produce velocity profiles with inflections. The suitability of the annular screen method of boundary layer generation for diffuser investigations was confirmed from the comparison with the approach length results.

Energy and pressure coefficients, as well as diffuser energy efficiency and the conversion efficiency, were found to depend on the diffuser angle $\beta$ and the momentum thickness ratio at inlet $\theta/D_0$. The latter emerged as one of the chief parameters controlling diffuser performance. Variation in the inlet shape parameter $H$ of the order of 20 per cent did not significantly affect the pressure recovery or the losses in the diffuser. For moderately thick boundary layers, $\theta/D_0 \times \beta < 0{\cdot}1$, the diffuser angle could be eliminated as a parameter by plotting the pressure coefficient against $\theta/D_0 \times \beta$. The Reynolds number based on diffuser inlet diameter was, for essentially incompressible flow, $2{\cdot}5 \times 10^5$ in all tests.

## 1. Introduction

Flow in diffusers is of considerable practical importance in turbines, pumps, fans, compressors, and other rotodynamic machines. At some stage of the passage through the machine there arises the problem of recovering kinetic energy, which cannot be sacrificed without detrimental effect on efficiency. The kinetic energy is converted to pressure energy by decelerating the flow in expanding passages—diffusers—of suitable contour.

The efficiency of this conversion process is of immediate interest since it affects machine performance. The resulting discharge flow is equally important if the diffuser is linked to a downstream component. Ideally, maximum pressure recovery and steady conditions of discharge are wanted, combined with a satisfactory velocity distribution at exit.

Even in their simplest versions, diffusers introduce a form of flow which at present defies analysis. Their design is therefore largely based on empirical data. Extensive research[1] has produced semi-empirical methods for calculating the turbulent boundary layer growth in a pressure gradient, but they are of limited value for analysing diffuser performance.

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Since rigid mathematical solutions are not available to determine the effect of a pressure gradient on the velocity distribution in turbulent flow, improved semi-empirical methods of calculation are required. A promising new approach has recently been presented by Ross[2] for two-dimensional flow, based on physical considerations of shear stress diffusion.

At the Mechanical Engineering Research Laboratory systematic investigations are in progress on straight conical diffusers to explore the possibility of extending such a method to three-dimensional flow and rough surfaces. Since from physical considerations and experimental evidence the inflow conditions are known to affect the performance of a diffuser, an initial phase of the experiments was to investigate this dependence in terms of boundary layer characteristics. In these tests the effects of variation in the boundary layer conditions at inlet on the pressure recovery and losses in two aluminium diffusers of 4:1 area ratio and 5 and 10 degrees total angle of expansion have been studied. Annular screens, in the form of projecting screen rings, and approach lengths of diffuser entry diameter have been used to thicken the boundary layer artificially and to produce variations in the inlet velocity distribution.

FIGURE 1. Diffuser rig.

NOTATION

| | |
|---|---|
| $D_0$ | pipe diameter at nominal entry to diffuser |
| $D_2$ | pipe diameter at end of diffuser |
| $A$ | area ratio $=(D_2/D_0)^2$ |
| $L$ | approach pipe length, nominal |
| $L_s$ | settling length |
| $\beta$ | diffuser angle |
| $X$ | distance along diffuser from ring of static tappings at station 0 |
| $Y$ | transverse distance from duct wall |
| $W$ | projecting screen ring width |
| $D_1$ | inner diameter of screen ring |
| $u$ | mean axial velocity at a point |
| $U$ | velocity outside boundary layer |
| $\overline{U}$ | average velocity, ratio of discharge to area |
| $R$ | pipe Reynolds number at diffuser entry $=D_0\overline{U}_0/\nu$ |
| $\frac{1}{2}\rho\overline{U}_0^2$ | mean dynamic pressure |
| $\Delta p, \Delta p_i$ | pressure difference between stations 0 and 2 for a real, and an ideal fluid |
| $C_p, C_{pi}$ | pressure coefficients $=2\dfrac{\Delta p}{\rho\overline{U}_0^2}$ , $2\dfrac{\Delta p_i}{\rho\overline{U}_0^2}$ |
| $\delta$ | boundary layer thickness, defined at $0{\cdot}99u/U$ |
| $\delta^*$ | displacement thickness of boundary layer $=\int_0^\delta\left(1-\dfrac{u}{U}\right)dy$ |
| $\theta$ | momentum thickness of boundary layer $=\int_0^\delta\left(1-\dfrac{u}{U}\right)\dfrac{u}{U}dy$ |
| $H$ | boundary layer shape parameter $=\dfrac{\delta^*}{\theta}$ |
| $\alpha$ | energy coefficient $=\dfrac{1}{\overline{U}^3\times\text{area}}\int_{\text{area}}u^3\times d\,(\text{area})$ |
| $\rho$ | density of medium |
| $\nu$ | kinematic viscosity |
| 0, 2 | suffixes denoting stations 0 and 2 |

## 2. Test Facilities

The test rig used in these initial investigations is shown in Figs. 1 and 2. Air was drawn through the arrangement by a 1·5 h.p. axial-flow fan having Ward-Leonard speed control. A honeycomb flow straightener and 20-mesh screen were installed in the entry section. The contraction following consisted of a 20-degree conical nozzle connected by a flared transition to the 7·5-inch diameter test section containing instrument traverse station 0.

The test diffusers were connected to the test section by equal length flared transitions, and discharged into a 15-inch diameter parallel settling duct connected downstream to the fan intake. The air was finally turned through 90 degrees in a vaned elbow and exhausted upwards.

Total pressure probes with rectangular orifices 0·025 by 0·125 inch and boundary layer type probes of orifice dimensions 0·007 by 0·05 inch were used in the traverses at stations 0 and 2. The static pressure was read at station 0 from a ring of static tappings in the plane of the probe mouth, from a series of tappings along the diffuser, and at station 2 from a ring of static tappings in the traverse plane. Tapping size was 1 mm.

Pressures were recorded on Betz projection and multi-tube manometers with a reading accuracy of

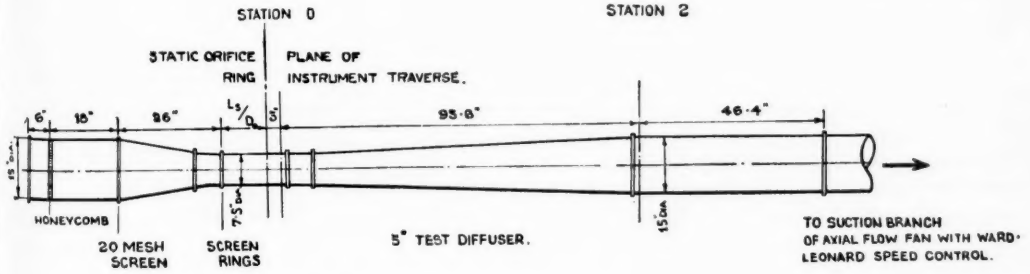


FIGURE 2. Arrangement of diffuser rig.

TABLE I

HAND-CUT SCREEN RINGS, 26 S.W.G.
SETTLING LENGTH $L_s = 1{\cdot}5D_0$

| *Nominal Screen Ring Depth, inch* | $D_1/D_0$ | 5° *Diffuser* | 10° *Diffuser* |
|---|---|---|---|
| 0 | 1·00 | * | – |
| 1/8 | 0·97 | * | – |
| 1/4 | 0·93 | * | – |
| 3/8 | 0·90 | * | – |
| 1/2 | 0·87 | * | – |
| 5/8 | 0·83 | * | – |
| 3/4 | 0·80 | * | – |
| 7/8 | 0·77 | * | – |
| 1 | 0·73 | * | – |

* Tested. – Not tested.

0·05 mm. and 0·05 inch water-gauge respectively. The multi-tube manometers were used only for comparative measurements in which the diffuser pressure distribution was recorded for different upstream conditions.

## 3. Test Programme and Procedure

In general, the turbulent velocity distribution depends both on the spatial flow history and on local conditions[2]. For a diffuser it was recognised at an early stage[3] that inflow conditions are particularly important as they determine the subsequent development of the flow. It has only recently been realised, as a result of the study by Robertson and Ross[4], that inflow conditions are as important as the diffuser angle in determining diffuser flow.

The objective of the present investigation was to establish the nature of the dependence of overall diffuser performance on inlet boundary-layer characteristics, and in particular on the shape parameter $H$. It was desired to produce wide variation in the inlet conditions within a moderate space.

Of the methods which have been used to thicken turbulent boundary layers[5], none seemed entirely suitable either due to inconvenience, or probable inability to repeat conditions reliably, or on the grounds of space. It was, therefore, decided to retard the flow in the boundary layer region by means of projecting screen rings. It was realised that the presence of the screen rings would change the turbulence pattern of the flow and might influence the occurrence of separation. However, for non-separating flow, the effect on overall diffuser performance was expected to be insignificant. The only precaution taken was to insert a settling length between screens and station 0 which prevented the screen rings influencing the static pressure tappings at the reference station.

All screen rings were made from 16-mesh woven wire cloth. For the exploratory tests they were hand cut, and soldered at the inner ring edge to avoid distortion. The settling length $L_s$ was $1{\cdot}5D_0$; nominal screen ring dimensions are given in Table I.

The rings used in the main series of tests, Table II, were cut on a lathe, and the bolt holes accurately located by means of a metal template, Fig. 3.

TABLE II

MACHINE-CUT SCREEN RINGS, 26 S.W.G.
SETTLING LENGTH $L_s = 3{\cdot}0D_0$

| *Nominal Screen Ring Depth, inch* | $D_1/D_0$ | 5° *Diffuser* | 10° *Diffuser* |
|---|---|---|---|
| 0 | 1·00 | * | * |
| 1/16 | 0·98 | * | – |
| 1/8 | 0·97 | * | * |
| 3/16 | 0·95 | * | * |
| 1/4 | 0·93 | * | * |
| 5/16 | 0·92 | * | – |
| 3/8 | 0·90 | * | * |
| 7/16 | 0·88 | * | * |
| 1/2 | 0·87 | * | * |
| 9/16 | 0·85 | * | – |
| 5/8 | 0·83 | * | * |
| 11/16 | 0·82 | * | – |
| 3/4 | 0·80 | * | * |
| 13/16 | 0·78 | * | * |
| 7/8 | 0·77 | * | * |
| 15/16 | 0·75 | * | – |
| 1 | 0·73 | * | * |

* Tested. – Not tested.

The screen rings were mounted between the flanges of the preceding contraction and the following settling length.

The longest approach length used with the 5-degree diffuser was approximately $19D_0$, while separation in the 10-degree diffuser restricted the upstream length to about $8D_0$. All tests were run at Reynolds number $\sim 2{\cdot}5 \times 10^5$, in the top speed range of the rig. With traverse instruments withdrawn, static pressures at the tapping rings and along the diffuser were recorded. Initially, traverse readings were taken on two perpendicular diameters at station 0. It was subsequently found that a careful traverse on one diameter was adequately representative, and readings were restricted to 60 points on the horizontal diameter. From these the inlet boundary layer parameters $\alpha_0$, $\delta_0^*$, $\theta_0$ and the mean

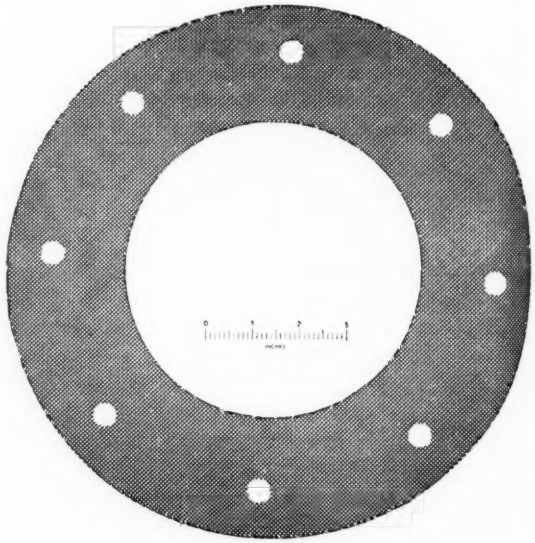

FIGURE 3. Screen ring
$D_1/D_0 = 0{\cdot}850$. $W = 0{\cdot}562$.

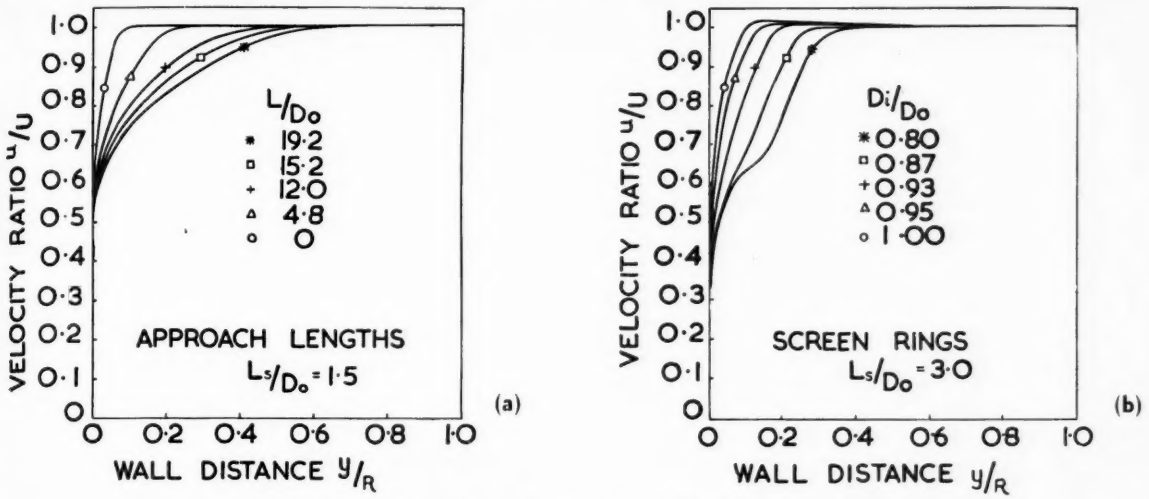


FIGURE 4. Velocity profiles produced by approach lengths and screen rings.

dynamic inlet pressure $\frac{1}{2}\rho\overline{U}_0^2$ were calculated. A similar procedure was adopted for the readings at station 2.

The diffuser pressure rise was conveniently measured as the pressure difference between the rings of static tappings at station 0 and 2. From Fig. 2 it can be seen that by this procedure the diffuser was debited with the pressure loss from the ring of tappings at station 0 to the geometric start of the diffuser, a distance of $L/D_0 \simeq 1{\cdot}25$. In comparing results with published data, this loss must be considered.

## 4. Presentation of Results

The so-called efficiency terms used really describe diffuser effectiveness, since they consider certain aspects only of diffuser action. No single diffuser efficiency is a complete criterion of diffuser performance.

The " pressure efficiency ":

$$\eta_p = \frac{d\nabla}{\Delta p_i} \equiv \frac{C_p}{C_{pi}} \quad . \quad . \quad . \quad (1)$$

relates the pressure regain for a real fluid to that for an ideal fluid in the same diffuser.

The " energy conversion efficiency ":

$$\eta_{conv} = \frac{C_p}{\alpha_0 - \alpha_2\left(\frac{D_0}{D_2}\right)^4} \quad . \quad . \quad (2)$$

is the ratio of the pressure rise in a diffuser to the resulting reduction in kinetic energy. A criterion useful for studying trends in diffuser performance results from equation (2) for $\alpha_2 = 1$. The term:

$$\eta^* = \frac{C_p}{\alpha_0 - \left(\frac{D_0}{D_2}\right)^4} \quad . \quad . \quad . \quad (3)$$

allows for actual inlet conditions but assumes an ideal velocity distribution at exit and so results in the lowest possible numerical value of equation (2).

The " energy efficiency " results from the equation of motion:

$$p_0 + \alpha_0 \tfrac{1}{2}\rho\overline{U}_0^2 = p_2 + \alpha_2 \tfrac{1}{2}\rho\overline{U}_2^2 + \kappa\alpha_0 \tfrac{1}{2}\rho\overline{U}_0^2 . \quad (4)$$

where $\kappa\alpha_0 \frac{1}{2}\rho\overline{U}_0^2$ is diffuser loss. Hence:

$$\eta_e \equiv 1 - \kappa = \frac{\Delta p + \alpha_2 \frac{1}{2}\rho\overline{U}_2^2}{\alpha_0 \frac{1}{2}\rho\overline{U}_0^2} \quad . \quad . \quad (5)$$

and determines diffuser losses. As is easily seen:

$$\eta_e > \eta_{conv} > \eta^* \quad . \quad . \quad . \quad (6)$$

If $\eta_D$ represents the various terms describing diffuser effectiveness,

$$\eta_D = \phi\,(C_p, \alpha_0, \alpha_2, A) \quad . \quad . \quad (7)$$

where the area ratio $A$ was a constant. In their turn $C_p$, $\alpha_0$ and $\alpha_2$ must depend on diffuser angle, surface texture and inlet conditions.

## 5. Discussion of Results

Examples of the approach length velocity profiles at station 0 are plotted in Fig. 4(*a*) and those produced by the screen rings in Fig 4(*b*). In a single parameter presentation of $u/U$ against $y/\theta$ the screen ring results showed fair agreement, in the range $1{\cdot}4 \leqslant H < 1{\cdot}7$, with results of a survey of existing data presented in this form in Ref. 6.

The resulting boundary layer characteristics are linearly dependent on approach lengths and screen ring dimensions, Figs. 5(*a*) and (*b*). The discontinuity in the screen ring values, Fig. 5*b*, was due to the settling length chosen. It did not, for instance, occur in the initial tests with the hand-cut rings for which the settling length ratio was $L_s/D_0 = 1{\cdot}5$, Fig. 6.

The effect of the difference in settling length for approach lengths and screen ring results in Figs. 5(*a*) and (*b*) is nominal only, and can be resolved simply by transposing the origin in Fig. 5(*a*) to $L/D_0 = 1{\cdot}5$. The resulting values for $\delta^*$ and $\theta$ are then identical with

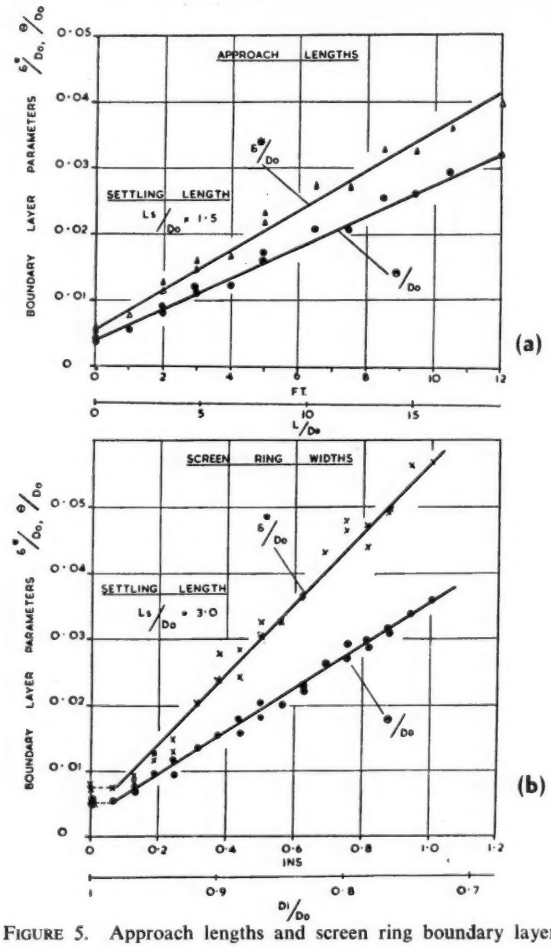


FIGURE 5. Approach lengths and screen ring boundary layer parameters.

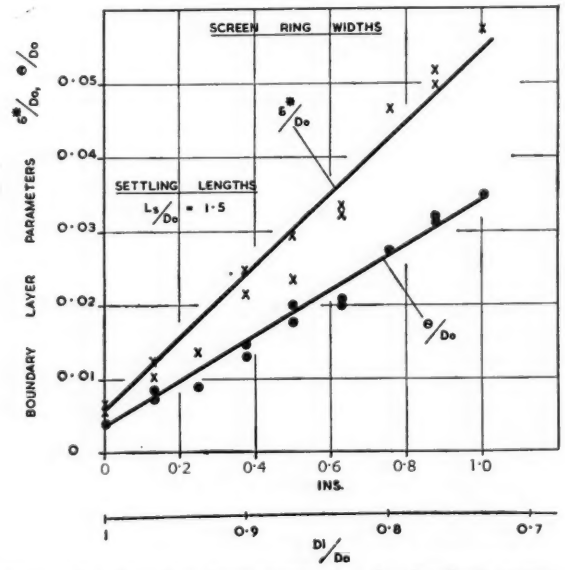


FIGURE 6. Boundary layer parameters for hand-cut screen rings.

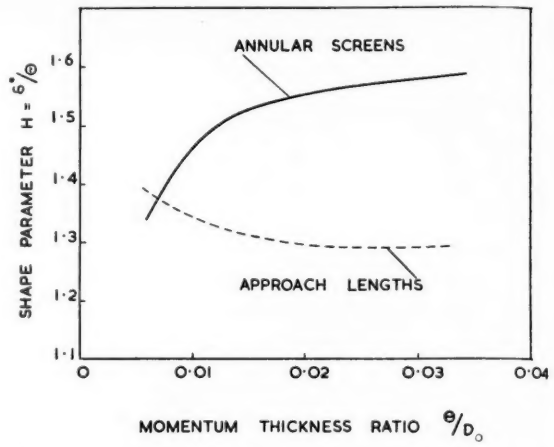


FIGURE 7. Variation of the shape parameter $H=\delta^*/\theta$ as a function of momentum thickness for approach lengths and annular screens.

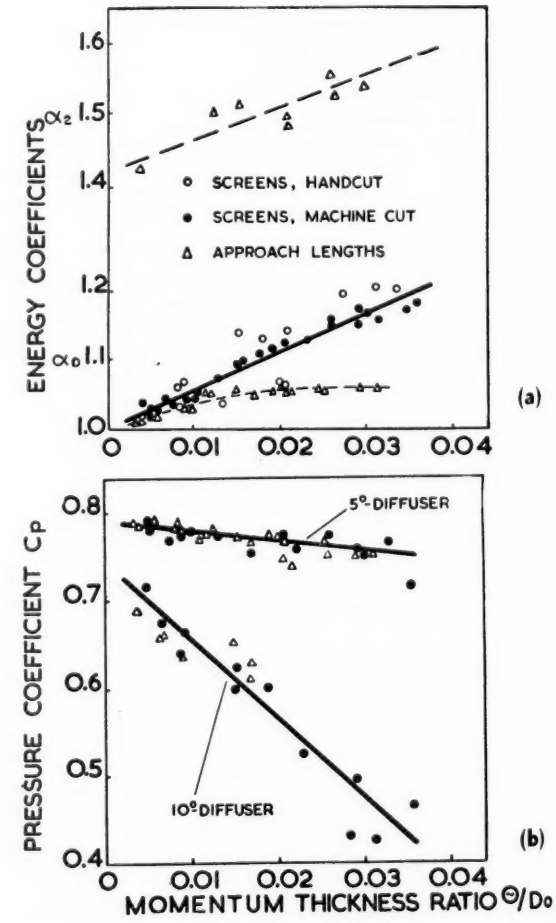


FIGURE 8. Energy and pressure coefficients against inlet momentum thickness.

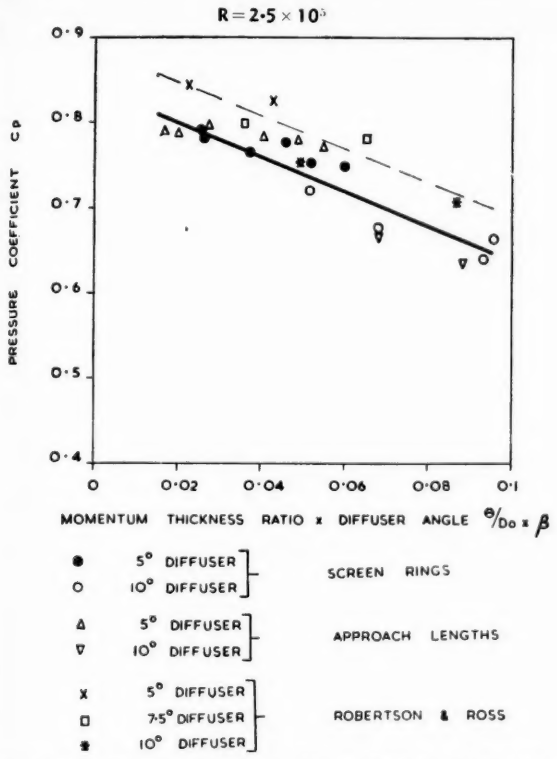


FIGURE 9. Pressure coefficient for moderately thick inlet boundary layers against $\theta/D_0 \times \beta$.

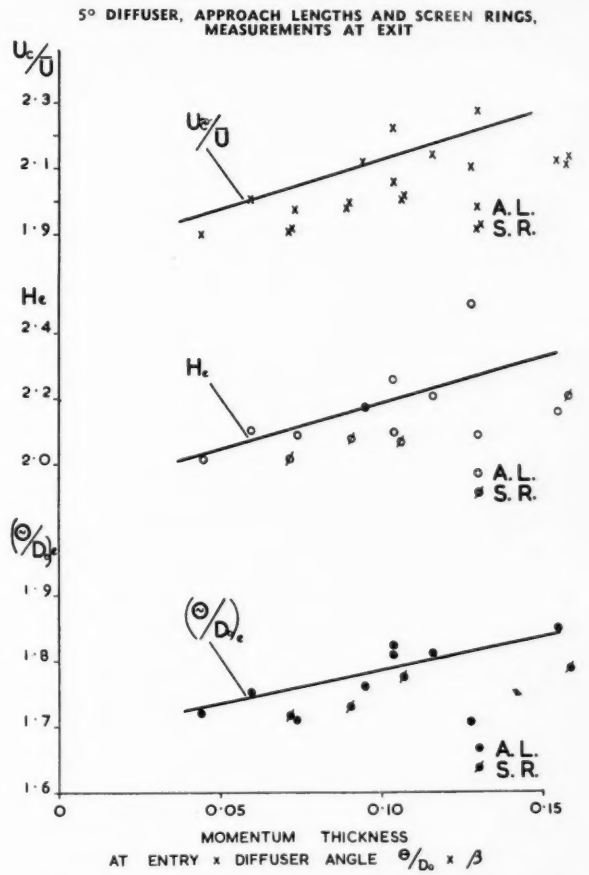


FIGURE 10. Variation of $(\theta/D_0)_e$, $H_e$ and $U_c/U$ as a function of momentum thickness at inlet.

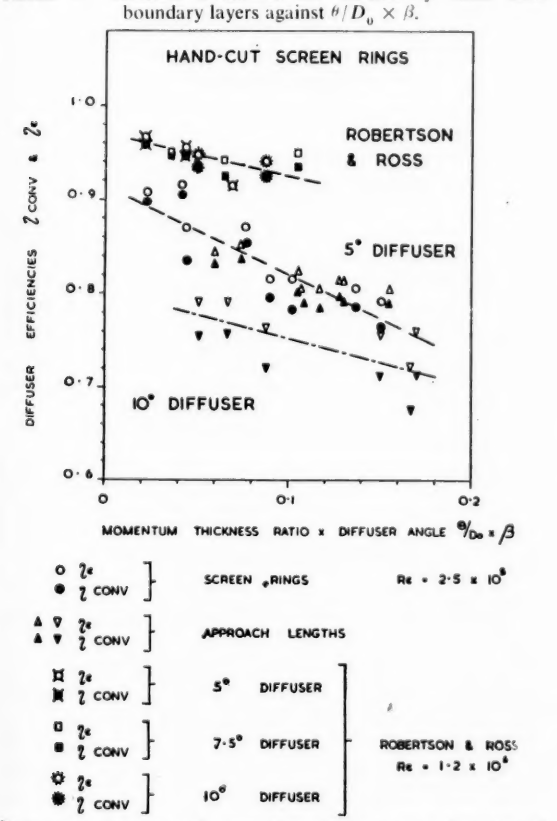


FIGURE 11. Energy and conversion efficiency as a function of $\theta/D_0 \times \beta$ for 5° and 10° diffuser.

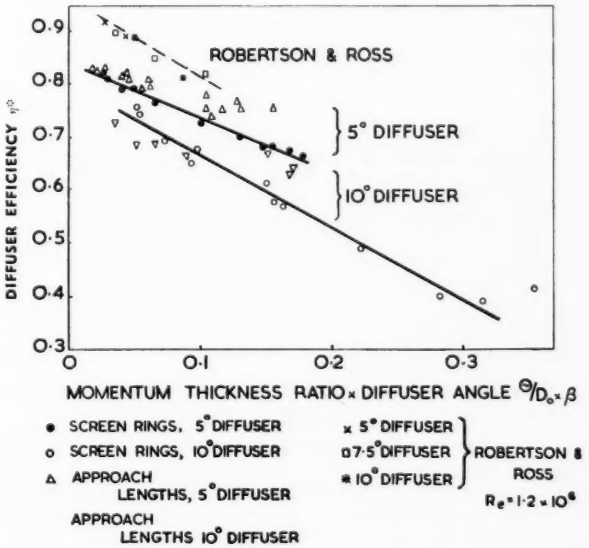


FIGURE 12. Diffuser efficiency $\eta^*$ for 5° and 10° diffuser for approach lengths and screen rings.

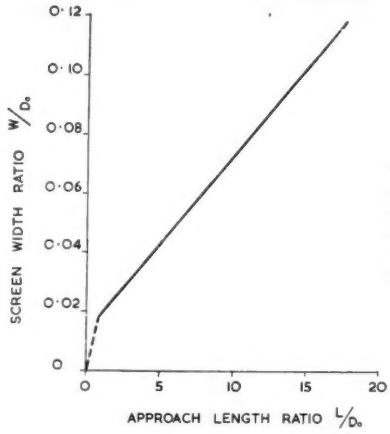


FIGURE 13 (*left*). Correlation of approach lengths and screen dimensions for equivalent momentum thickness $L_s/D_0 = 3{\cdot}0$.

those for the no-screen case. For the screen rings, however, the settling length chosen is an integral feature which cannot be eliminated.

The major difference in the results of the two methods is apparent in Fig. 7. While the shape parameter for the approach lengths decreases to a constant value of $H \simeq 1{\cdot}29$, the screen ring values increase steadily with increasing momentum thickness ratio. The maximum difference between the two shape-parameter curves, at $\theta/D_0 \simeq 0{\cdot}032$, was about 22 per cent.

This is reflected in Fig. 8(*a*) where the energy coefficient $\alpha_0$ for the approach lengths tends to a constant value with increasing momentum thickness ratio, while the screen ring values lie on a straight line. The accentuated scatter in the results obtained with the hand-cut screen rings can be seen. On the same graph, $\alpha_2$ at diffuser exit is shown to depend also on $\theta/D_0$ at inlet. This result for the approach lengths was confirmed in the other tests, and by published data[7].

For a constant area ratio the pressure coefficient $C_p$ is representative of the " pressure efficiency " $\eta_p$. Results for the 5- and 10-degree diffuser plotted in Fig. 8(*b*) show $C_p$ to depend on inlet momentum thickness. The agreement between approach lengths and screen ring values suggests that a variation of the shape parameter $H$ at inlet, of the order of 20 per cent, had neither systematic nor significant effects on the pressure recovery in the diffuser. The approach length results for the 10-degree diffuser were to some extent affected by the occurrence of separation. This seems analogous to pipe flow results, for which the coefficient of friction has been shown to depend on the Reynolds number based on momentum thickness[8], but it is in disagreement with the findings of Ludwieg and Tillmann[9], which, for non-separation flow, lead one to expect $C_p = f(R_\theta, H)$.

By plotting $C_p$ against $\theta/D_0 \times \beta$, a universal presentation results for $\theta/D_0 \times \beta < 0{\cdot}1$, Fig. 9. Values taken from Ref. (7) and extrapolated for Reynolds number $\simeq 2{\cdot}5 \times 10^5$ showed the same linear dependence on $\theta/D_0 \times \beta$ and nearly identical slope. For a quantitative comparison it must be remembered that in the

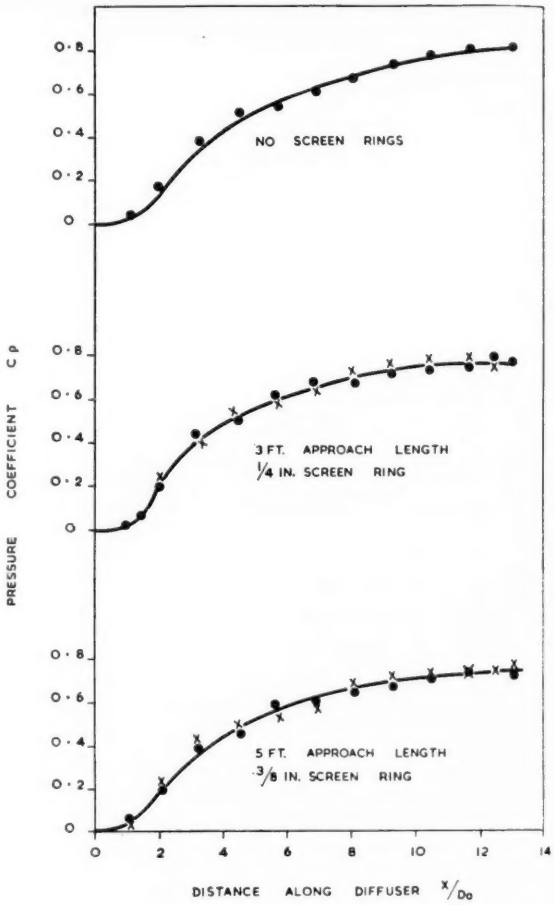


FIGURE 14. Pressure recovery in 5° diffuser settling length $L_s/D_0 = 3{\cdot}0$.

M.E.R.L. tests the pressure loss over $L/D_0 \simeq 1{\cdot}25$ has been included.

For both screen ring and approach length tests the ratio of centre line to mean velocity, the momentum thickness $\theta$, and the shape parameter $H$ at diffuser exit were also found to depend on inlet momentum thickness, which thus emerges as a major parameter controlling diffuser performance, Fig. 10.

This is confirmed in Fig. 11, where conversion efficiency and energy efficiency have been plotted as a function of $\theta/D_0 \times \beta$. Again there is no evidence to suggest that results were significantly affected by the variation of the shape parameter at inlet. The increased scatter can be traced to the exit measurements from which $\alpha_2$ was determined, and in the case of the 10-degree diffuser, to the occurrence of separation. The variation at a higher Reynolds number, in the results of Robertson and Ross with inlet momentum thickness, is similar, although more gradual than for the M.E.R.L. results and apparently independent of diffuser angle.

The efficiency $\eta^*$ for screen ring and approach length results is plotted in Fig. 12, together with values calculated from Refs. (7) and (10). The latter are again

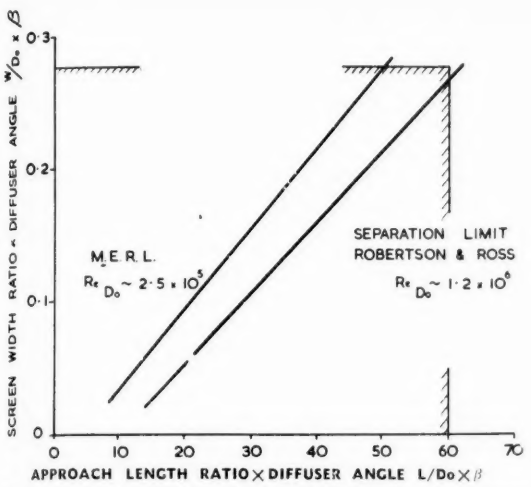


FIGURE 15. Correlation of approach lengths and screen dimensions for equivalent momentum thickness.
Approach lengths $L_s/D_0 = 0$. Screen rings $L_s/D_0 = 3{\cdot}0$.

independent of the diffuser angle. The effect of the difference in the $z_0$ values for screen rings and approach lengths is reflected in the respective $\eta^*$ results, $\theta/D_0$ however still being the controlling parameter for the diffuser angle given.

Screen ring results and approach length values have been correlated in Fig. 13 for a common settling length of $3{\cdot}0D_0$, the basis being identity of the $\theta/D_0$ values. An approach length of 2·5 feet is seen to correspond approximately to a $\frac{1}{4}$-inch screen ring, that of a 4·5 foot approach length to a screen ring of $\frac{3}{8}$-inch projecting width. The pressure distributions along the 5-degree diffuser have been compared in Fig. 14 for screen rings of these dimensions, and approach lengths of 3 and 5 feet respectively, these being approximately the nominal approach lengths of the tests with settling length $L_s = 1{\cdot}5D_0$. Less stress is laid on the evident agreement than on the fact that the presence of the screen rings did not distort the pressure regain in the diffuser. Readings for these plots were taken from photographic records of multi-tube manometer readings, and showed some scatter when plotted on a large scale. The comparable results from screen rings and approach lengths fell into two nearly identical bands.

For a comparison with published results, the settling length was added to the approach lengths, and results again related to screen ring dimensions, Fig. 15. No attempt was made to correct the lengths so obtained for the boundary layer growth in the preceding contraction, as was done in Ref. 4.

From their tests at Reynolds number $= 1{\cdot}2 \times 10^6$, Robertson and Ross suggested the occurrence of separation at $L/D_0 \times \beta \geq 60$. There is some evidence to suggest that in the M.E.R.L. tests this value was nearer 50. If this figure is tentatively accepted, it follows from Fig. 15 that separation in the 5-degree diffuser should occur if a screen ring of approximately 0·4-inch projecting width is used, or for approximately 0·2-inch screen width in the case of the 10-degree diffuser.

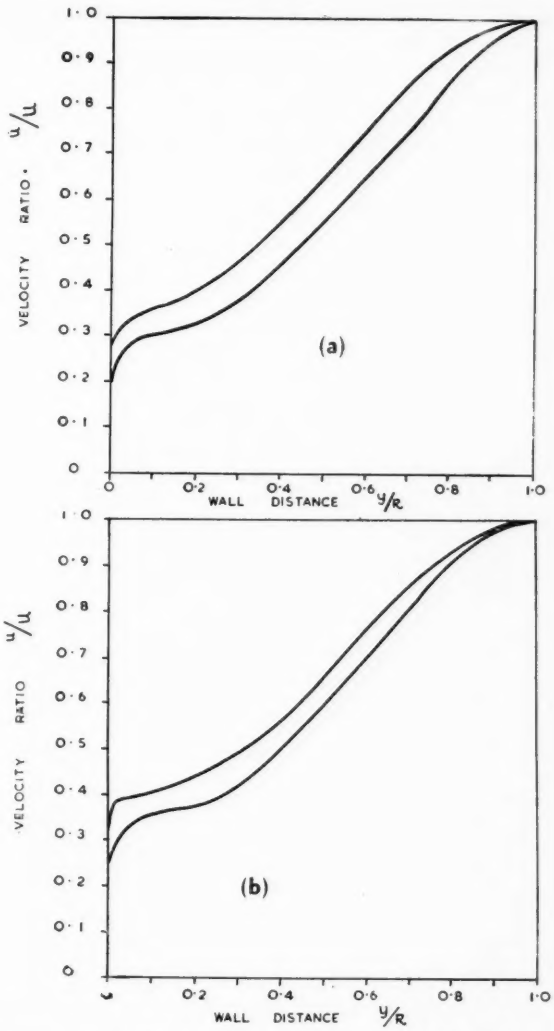


FIGURE 16. Velocity profile contours at the exit of the 5° diffuser for approach lengths and screen rings. (*a*) Approach lengths. (*b*) Screen rings.

Without detailed velocity traverses along the diffuser, it is a matter of speculation when the onset of separation occurs. From the downstream traverse readings, it is believed that no significant separation occurred in tests with screen rings of less than $\frac{7}{8}$-inch projecting width. From the comparison of velocity contours at the exit of the 5-degree diffuser, Figs. 16(*a*) and (*b*), it is apparent that the screen rings produced higher near-wall velocities than the approach lengths, probably due to screen turbulence. A comparison with Figs. 4(*a*) and (*b*) also illustrates the tendency of the diffuser to equalise differences in the inlet velocity distributions.

## 6. Conclusions

1. A novel method of generating specific boundary layer conditions by means of projecting annular screens has been applied to diffuser research.

2. Diffuser energy efficiency and the terms describing diffuser effectiveness depended on the momentum thickness ratio at inlet, irespective of the inlet velocity distribution.

The controlling influence of $\theta/D_0$ extended to momentum thickness, velocity distribution and shape parameter at exit of the diffuser for flow without extensive separation.

3. Experimental evidence from a comparison of approach lengths and screen ring results on the basis of equivalent momentum thickness at inlet showed no significant effects of a 20 per cent variation in the inlet shape parameter on pressure recovery or losses in the diffuser.

4. The presence of the screen rings is believed to have delayed the onset of separation.

ACKNOWLEDGMENT

The work described has been carried out as part of the research programme of the Mechanical Engineering Research Board of the Department of Scientific and Industrial Research. The authors acknowledge the permission of the Director of Mechanical Engineering Research to publish the paper.

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# TECHNICAL NOTES

*Contributions to this Section of the* JOURNAL *will be eligible for Journal Premium Awards and will normally be published within three months of being received.*

## *An Electronic Instrument for the Accurate Measurement of the Frequency of Structural Oscillations*

by

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(*Royal Aircraft Establishment*)

AN INSTRUMENT is described which measures the time duration of a specified number of complete cycles of an oscillation over the frequency range 0·1 cycles per second to 500 cycles per second. The accuracy of the reading is dependent on the frequency measured and the number of cycles taken; but, in most cases, an accuracy better than 0·1 per cent is obtainable. The construction of the instrument is described and circuit diagrams given.

### INTRODUCTION

An accurate method of measuring structural frequencies was required in flutter and derivative work, particularly in the latter, where it is necessary with certain techniques to repeat a forced oscillation with a high degree of accuracy. Available instruments were either not compact enough for use in this work or were insufficiently accurate and did not cover the required frequency range. A portable electronic instrument with a high standard of accuracy has, therefore, been developed for this purpose.

This instrument measures the time duration of a selected number of complete cycles of the structural oscillation against a highly stable time base, consisting of a valve-maintained tuning fork oscillating at 1,000 cycles per second. It is necessary for the structural oscillation to be converted into an electrical signal of approximately 5 volts amplitude. In measuring frequencies below ten cycles per second the time interval for one complete cycle is measured; for frequencies between ten and five hundred cycles per second the time of either ten or one hundred complete cycles can be measured, greater accuracy being obtained by taking the larger number of cycles. In all cases the answer is displayed as a number on electronic decade scaling tubes and can, therefore, be read off quickly and easily.

An automatic control is included which returns the reading of the scaling tubes to zero and re-measures the selected time interval every ten seconds. Over most of the frequency range this leaves sufficient time for the operator to take note of the readings. Should it be desirable for the reading to be left on for a longer time, or should the operator need to initiate the measurement at some particular instant (*i.e.* at the start of a decaying oscillation), the automatic control can be switched out and a normal press-button control used.

A " test " switch is provided to enable the instrument to measure the period of the mains supply. This checks that all electronic scaling tubes and their associated amplifying valves are working correctly and provides a means of checking the operation of the remaining circuits.

*Received 21st November 1956*

### PRINCIPLE OF OPERATION

Referring to the block diagram in Fig. 1 the electrical signal frequency which is to be measured is passed first to the Pulse Unit. This unit supplies two trains of positive voltage pulses, one train at every tenth cycle of the input frequency and the other at every hundredth cycle. Either of these two trains of pulses can be selected by the change-over switch shown and passed to the Electronic Switch Unit.

The latter is placed between the 1,000 c.p.s. time base oscillator and the Register Unit and is, initially, open. The first positive pulse to arrive from the Pulse Unit closes the switch and the Register begins to count the number of cycles received from the 1,000 cycles per second time base oscillator. The second positive pulse opens the switch once more and the Register stops, showing the number of thousandths of a second which have elapsed between the two pulses. From the Register, by inserting the appropriate decimal point, the duration of the period of one complete cycle of the frequency measured can be read off.

The Automatic Reset Unit returns the Register to zero and the electronic switch to its initial position, ready to begin a re-count at the next positive pulse received. This operates at ten-second intervals but can be replaced by manual control.

The above method of operating the Electronic Switch is used for input frequencies between ten cycles per second and 500 cycles per second. Below ten cycles per second an external battery and make or break contact fitted to the oscillating structure are required. The Electronic Switch Unit is then operated directly by pulses from the contacts, and the Pulse Unit itself is switched off. The Register records the time between two successive pulses, corresponding to one complete cycle of the low frequency oscillation.

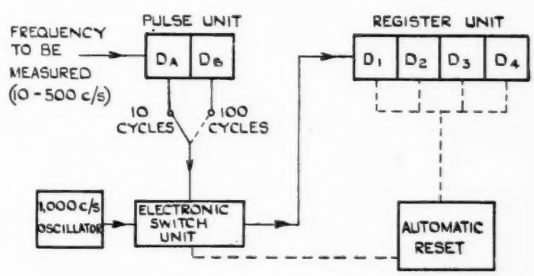



FIGURE 1. Block diagram.

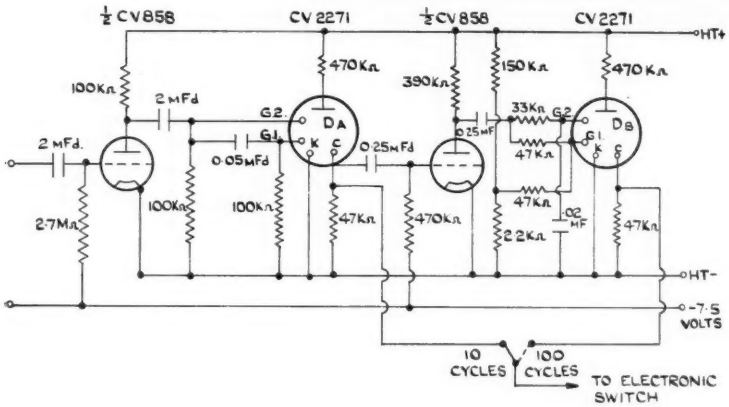
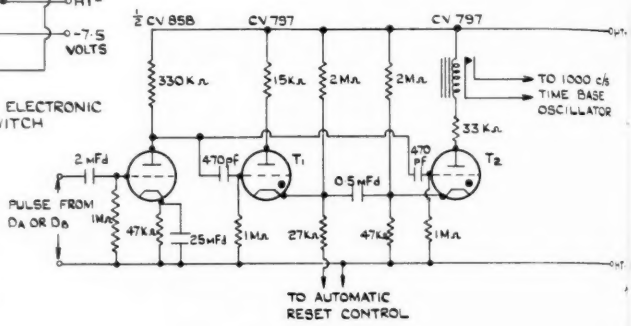



FIGURE 2 (*left*). Circuit diagram of pulse unit.

FIGURE 3 (*below*). Electronic switch unit. Patent application No. 17,401/55.




PULSE UNIT

The circuit diagram of the Pulse Unit is shown in Fig. 2. The incoming oscillating signal to be measured is first amplified by the triode circuit shown and passed directly to $G.2$ of the decade scaling tube, $D_A$, and through a phase-advancing network to $G.1$ of the same tube.

This electronic scaling tube is a system of electrodes so arranged in a glass envelope that, from the top, a red glowing spot can be seen to move in ten steps comprising a circle, when suitable voltage pulses are applied to it.

Each guide $G.1$ and $G.2$ consists of ten pins joined together, and the cathode $K$ consists of nine pins. The cathode $C$ is a separate pin positioned at the " zero " point in the counting sequence. These guides and cathodes are positioned sequentially in a circle as viewed from the top of the tube. A common anode is fixed at the centre of this circle. When supplied with voltage in a suitable circuit a glow discharge takes place between the anode and one pin of the most negative set of circumferential pins. If any one of the sets of guide or cathode pins is then made more negative than the other the glow discharge will transfer to the nearest of the negative pins. By a suitable arrangement of negative pulses the glow can thus be made to transfer in a clockwise direction from cathode to cathode in a total of ten steps. The tenth position is the separate cathode $C$ which indicates " zero " and " ten." When the glow reaches the cathode $C$ the top of the 47 kilohms resistor shown receives a positive pulse which is passed for amplification to a triode valve and also taken off through a change-over switch. As the glow is continually being driven around at the input frequency the cathode $C$ provides a positive pulse for every ten input cycles.

After amplification and inversion by the triode valve the positive pulses from the cathode are passed, through suitable phase-shifting networks, to the guides of the second scaling tube $D_B$. This tube thus counts at one tenth the speed of the tube $D_A$. As the glow discharge passes through its cathode $C$ it will also supply a positive pulse, but at the rate of one for every 100 input cycles. These pulses are also taken off through the change-over switch.

These two tubes are not returned to zero by the Automatic Reset or press-button. The fact that they are continually counting supplies a means of observing that the input frequency is being passed through smoothly and that the positive pulses are being supplied correctly for operation of the controlled electronic switch.

Ideally, the input amplitude required from the signal being measured is five volts, but it can be as low as one volt over the middle of the frequency range.

ELECTRONIC SWITCH UNIT

The circuit diagram of this switch is shown in Fig. 3. Positive pulses from the cathode of $D_A$ or $D_B$, as chosen by the change-over switch shown in Fig. 2, are first amplified. This produces a square wave at the anode of the amplifying triode. This square wave is differentiated by the capacitor-resistor circuits in the grids of the two thyratron valves. The differentiation is separate for the two valves to avoid interaction between them. Initially thyratron $T_1$ is off and $T_2$ is passing an anode current which holds the relay contacts in its anode circuit open. The first positive pulse to arrive switches $T_1$ on and, in doing so, switches $T_2$ off through the 0·5 mFd capacitor connecting their cathodes. This allows the relay contacts to close and completes the circuit for the 1,000 cycles per second time base.

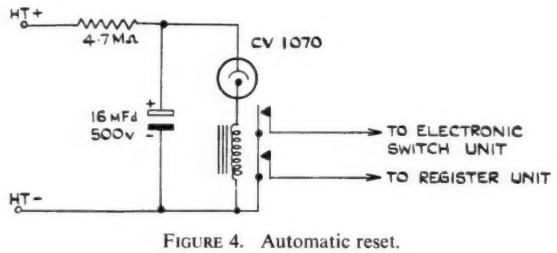



FIGURE 4. Automatic reset.

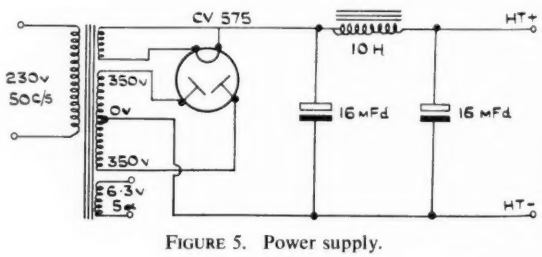



FIGURE 5. Power supply.

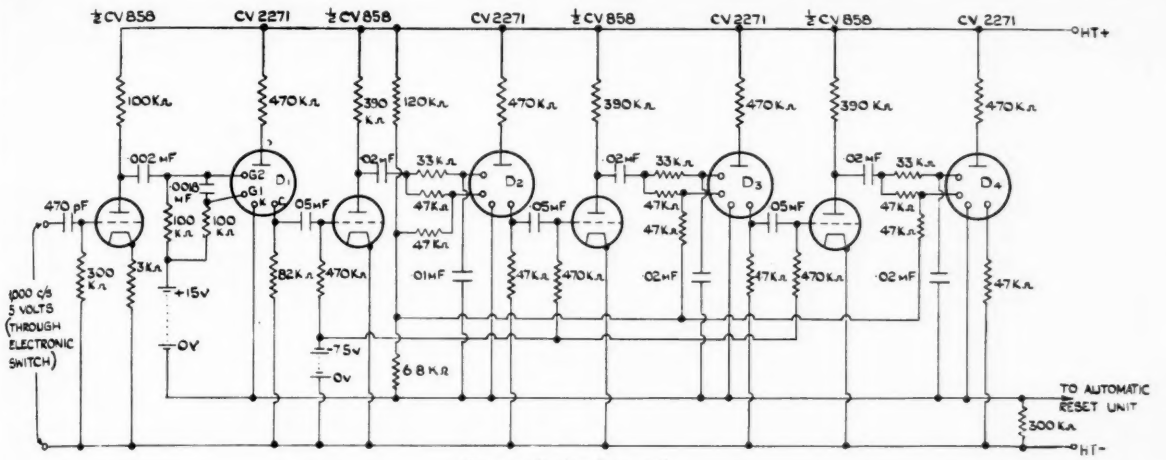



FIGURE 6. Register unit.

The second positive pulse now fires $T_2$ but, because of the difference in the two cathode circuits, this does not switch $T_1$ off. Both thyratrons, therefore, remain fired and the relay contacts open once more.

The circuit is now locked until the Automatic Reset Unit opens the contacts in the cathode circuit of $T_1$. Then $T_1$ is again switched off and, when the contacts in its cathode circuit re-close, is ready to repeat the operation.

### AUTOMATIC RESET UNIT

This circuit (Fig. 4) is one in which a 16 mFd electrolytic capacitor is charged slowly through a resistor from the H.T. supply. When the charge on the capacitor reaches approximately 110 volts the gas-discharge tube in parallel with it fires and the resulting current through the relay operates the relay contacts. These open while the relay is energised, the time constant of the circuit being such that the contacts will remain open sufficiently long for the Register Unit scaling tubes to return to zero and the thyratron in the Electronic Switch to clear.

### POWER SUPPLY

The power supply is shown in Fig. 5 and delivers 25 milliamps of H.T. current and 3·5 amps at 6·3 volts a.c. No additional voltage stabilisation was found to be necessary.

### THE REGISTER UNIT

The Register Unit consists of four electronic scaling tubes and associated amplifying triodes (Fig. 6). The 1,000 cycles per second input from the time base oscillator is amplified and used to drive the first scaling tube ($D_1$) at 1,000 cycles per second. The cathode circuit of the first tube provides positive pulses which are amplified and inverted to drive the second tube at 100 cycles per second, in the same way as for the pulse unit. Similarly the third is driven at ten cycles per second and the fourth at one cycle per second. When the 1,000 cycles per second supply is interrupted all scaling tubes remain steady, reading the total number of cycles which have been received.

During the counting period the 300 kilohms resistor (shown in the bottom right hand corner of Fig. 6) is short-circuited by contacts in the Automatic Reset Unit. When the Reset Unit operates, the shorting contacts open and the 300 kilohms resistor has to carry the total current of all circuits connected to it. As the guides and cathodes of the four scaling tubes are connected to the positive end of the 300 kilohms resistor (except the separate cathode *C* in the zero position), the glow discharge is forced to move to the zero cathode.

When the Reset Unit de-energises and the 300 kilohms resistor is again short-circuited the glow remains at the zero position and the Register is ready to recount.

### TIME BASE OSCILLATOR

A 1,000 cycles per second valve-maintained tuning fork providing a sine wave output of five volts amplitude is used with the equipment described. Alternative sources of frequencies up to 2,000 cycles per second could be used if required.

### CONCLUDING REMARKS

The instrument can be used with a suitable arrangement of external break or make circuits to measure the duration of any time interval up to a maximum of ten seconds (the limit of the Register). This, with the facility of varying the time base, widens its possible applications beyond those described in this Note.

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# *A Method for Calculating the Exhaust Port Area for Two-Stroke Cycle Engines*

by

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THE DESIGN of the exhaust ports of a two-stroke cycle engine is mainly based on the area required to reduce the cylinder pressure at the end of the expansion stroke to scavenge air pressure in the minimum practicable time. The flow through the exhaust ports is both sonic and subsonic; in the former case the flow is independent of the exhaust pipe conditions but not in the latter case. In the first stage of the design, however, the exhaust pipe

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conditions may be assumed to be constant when calculating the port area, subsequent calculations of the pressure drop allowing for the pipe size may then be made by the methods suggested by Wallace[1], Cole[2], or Benson[3]. In the following Note formulae are developed for estimating the port area neglecting the exhaust pipe size.

A number of methods have been suggested for calculating the exhaust port area; in nearly all cases the equations derived require graphical integration, or only apply when the ratio of specific heats $\gamma$ is 1·4. In the following treatment an exact solution to the equation for sonic flow is given for all values of $\gamma$; for subsonic flow an exact solution is given for all values of $\gamma$ which satisfy the equation $\gamma=(m+2)/m$ where $m$ is an integer.

NOTATION

| | |
|---|---|
| $a$ | speed of sound |
| $i$ | specific enthalpy |
| $n$ | r.p.m. |
| $p$ | pressure |
| $t$ | time |
| $u$ | velocity |
| $A_c$ | cylinder cross-sectional area |
| $L$ | cylinder length |
| $R$ | gas constant |
| $V$ | volume |
| $W$ | weight |
| $\rho$ | density |
| $\gamma$ | ratio of specific heats |
| $\alpha$ | crank angle |
| $\phi$ | ratio $\dfrac{\text{effective port area}}{\text{cylinder cross-sectional area}}$ |

*Suffices*

| | |
|---|---|
| e | constant exhaust back pressure |
| c | cylinder |
| t | throat or vena contracta |
| R | release conditions |
| 1 and 2 | limits of integration usually corresponding to cylinder release pressure and scavenge air pressure, or crank angle at exhaust port open and scavenge port open respectively |

*Parameters*

$$m=\frac{2}{\gamma-1} \qquad r=\frac{p_c}{p_e}$$

$$x=\frac{a_t}{a_c}=\left(\frac{p}{p_c}\right)^{\frac{\gamma-1}{2\gamma}} \text{ or } \left(\frac{p_e}{p_c}\right)^{\frac{\gamma-1}{2\gamma}} \text{ or } r^{-\frac{\gamma-1}{2\gamma}}$$

It is assumed that (*a*) the pressure is uniform throughout the cylinder, (*b*) the velocity in the cylinder is negligible, (*c*) the expansion is isentropic in the cylinder and across the ports, (*d*) the exhaust back pressure is constant, and (*e*) the cylinder volume is constant. The conditions in the cylinder and at the vena contracta or throat are then equated, the former corresponding to stagnation conditions. The fundamental equations are:

Mass change in cylinder:

$$\frac{dW_c}{W_c}=\frac{dp_c}{p_c}+\frac{dV_c}{V_c}-\frac{dT_c}{T_c} \quad . \quad . \quad (1)$$

Mass flow from cylinder through ports:

$$dW_c=-\phi A_c\rho_t u_t dt \quad . \quad . \quad . \quad (2)$$

Isentropic state equations:

$$\frac{dp_c}{p_c}=\frac{\gamma}{\gamma-1}\cdot\frac{dT_c}{T_c}=\frac{2\gamma}{\gamma-1}\cdot\frac{da_c}{a_c} \quad . \quad (3)$$

$$\left(\frac{p_t}{p_c}\right)^{\frac{\gamma-1}{2\gamma}}=\left(\frac{\rho_t}{\rho_c}\right)^{\frac{\gamma-1}{2}}=\frac{a_t}{a_c}=x \quad . \quad . \quad (4)$$

Theorem of conservation of energy:

$$i_c=i_t+\frac{u_t^2}{2} \qquad i=\frac{a^2}{\gamma-1}$$

therefore $$a_c^2=a_t^2+\frac{\gamma-1}{2}u_t^2 \quad . \quad . \quad . \quad (5)$$

Three cases will be discussed, namely, sonic flow through the ports, subsonic flow through ports, and combined sonic and subsonic flow.

SUBSONIC FLOW THROUGH THE PORTS

For a constant cylinder volume $dV_c=0$.

Combining equations (1), (3) and (4) and noting $m=\frac{2}{\gamma-1}$ we have

$$dW_c=mV_c\frac{\gamma p_c}{a_c^3}\cdot da_c \quad . \quad . \quad . \quad . \quad (6)$$

noting $$\rho_t=\rho_c\left(\frac{a_t}{a_c}\right)^m=\rho_c x^m \quad \text{from equation (4)}$$

and $$u_t=a_c m^{\frac{1}{2}}(1-x^2)^{\frac{1}{2}} \quad \text{from equation (5)}$$

equation (2) becomes

$$dW_c=-\phi A_c\rho_c a_c m^{\frac{1}{2}}x^m(1-x^2)^{\frac{1}{2}}dt \quad . \quad (7)$$

equating (6) and (7) we have

$$\frac{\sqrt{m}\cdot da_c}{a_c^2 x^m(1-x^2)^{\frac{1}{2}}}=-\frac{\phi}{L}\cdot dt. \quad . \quad . \quad (8)$$

Now $$x=\frac{a_t}{a_c}=\frac{a_t}{a_R}\cdot\frac{a_{cR}}{a_c}=\frac{x_{cR}a_{cR}}{a_c}$$

where $a_{cR}$ = speed of sound in cylinder at release

$$x_{cR}=\frac{a_t}{a_{cR}}=\left(\frac{p_t}{p_{cR}}\right)^{\frac{\gamma-1}{2\gamma}}=\left(\frac{p_c}{p_{cR}}\right)^{\frac{\gamma-1}{2\gamma}}=\text{constant}$$

with $$\frac{x}{dx}=-\frac{da_c}{a_c}$$

equation (8) becomes on integration

$$\sqrt{m}\int_{x_{c1}}^{x_{c2}}\frac{dx}{x^m(1-x^2)^{\frac{1}{2}}}=\frac{x_{cR}a_{cR}}{L}\int_{t_1}^{t_2}\phi\cdot dt \quad . \quad (9)$$

If $m$ is an integer the solution of the left hand side of equation (9) is

$$\sqrt{m}\int_{x_{c1}}^{x_{c2}}\frac{dx}{x^m(1-x^2)^{\frac{1}{2}}}=$$

$$=-\sqrt{m}\left[\frac{1}{(m-1)}\cdot\frac{\sin\theta}{\cos^{m-1}\theta}+\frac{m-2}{m-1}\int\sec^{m-2}\theta\cdot d\theta\right]_{x_{c1}}^{x_{c2}}$$

where $x=\cos\theta$

or

$$\sqrt{m}\int_{x_{c1}}^{x_{c2}}\frac{dx}{x^m(1-x^2)^{\frac{1}{2}}}=$$

$$=-\sqrt{m}\left[\frac{1}{(m-1)}\cdot\frac{(1-x^2)^{\frac{1}{2}}}{x^{m-1}}-\frac{m-2}{m-1}\int\frac{dx}{x^{m-2}(1-x^2)^{\frac{1}{2}}}\right]_{x_{c1}}^{x_{c2}}$$

the term $\int\frac{dx}{x^{m-2}(1-x^2)^{\frac{1}{2}}}$ is reduced in the same manner as above.

It is more useful to express the time $t$ in terms of crank angle $\alpha$ and speed r.p.m. ($n$); the right hand side of equation (9) becomes

$$\frac{x_{cR}a_{cR}}{6nL}\int \phi d\alpha$$

The solution to equation (9) is therefore

$$\int \phi d\alpha = -\frac{6nL}{x_{cR}a_{cR}}\sqrt{m}\left[\frac{1}{(m-1)}\cdot\frac{(1-x^2)^{\frac{1}{2}}}{x^{m-1}} - \frac{m-2}{m-1}\int\frac{dx}{x^{m-2}(1-x^2)^{\frac{1}{2}}}\right]_{x_{c1}}^{x_{c2}} \quad . \quad . \quad . \quad . \quad . \quad (10)$$

To cover the range of $\gamma$ for internal combustion engines values of $m$ would be 5, 6, 7 corresponding to $\gamma = 1{\cdot}400$, $1{\cdot}333$, $1{\cdot}286$ respectively.

A more useful form of equation (10) would be in terms of the pressure ratio $r = p_c/p_e$ where $p_e = p_t =$ constant exhaust back pressure. For the three values of $\gamma$ given above, assuming air to be the working fluid equation (10) becomes

$\gamma = 1{\cdot}4$

$$\frac{\sqrt{T_{c1}}}{r_{c1}^{1/7}}\cdot\frac{1}{nL}\int\phi d\alpha = -0{\cdot}03416\left[r^{2/7}(1-r^{-2/7})^{\frac{1}{2}}(2r^{2/7}+3) + 6{\cdot}909\log_{10}\left(\tan\left(\frac{\theta}{2}+\frac{\pi}{4}\right)\right)\right]_{r_{c1}}^{r_{c2}} \quad . \quad . \quad . \quad . \quad . \quad . \quad (11)$$

where $\cos\theta = r^{-1/7}$

$\gamma = 1{\cdot}333$

$$\frac{\sqrt{T_{c1}}}{r_{c1}^{1/8}}\cdot\frac{1}{nL}\int\phi d\alpha = -0{\cdot}06143\left[(r^{1/4}-1)^{\frac{1}{2}}\left(r^{1/2}+\frac{4}{3}r^{1/4}+\frac{8}{3}\right)\right]_{r_{c1}}^{r_{c2}} \quad (12)$$

$\gamma = 1{\cdot}286$

$$\frac{\sqrt{T_{c1}}}{r_{c1}^{1/9}}\cdot\frac{1}{nL}\int\phi d\alpha = -0{\cdot}33784\left[\frac{1}{6}r^{1/9}(r^{2/9}-1)^{\frac{1}{2}}\left(r^{1/9}+\frac{5}{4}r^{2/9}+\frac{15}{8}\right) + 0{\cdot}7197\log_{10}\tan\left(\frac{\theta}{2}+\frac{\pi}{4}\right)\right]_{r_{c1}}^{r_{c2}} \quad . \quad (13)$$

where $\cos\theta = r^{-1/9}$

$r_{c1}$ release pressure ratio
$r_{c2}$ scavenge pressure ratio or cylinder pressure ratio at any point in the exhaust blowdown
$T_{c1}$ temperature in cylinder at release in °F abs.
$n$ r.p.m.
$L$ cylinder length in feet
$\int\phi d\alpha$ effective exhaust port area times crank angle expressed as a ratio of port area to cylinder cross-sectional area $= \int\frac{A_p}{A_c}\cdot d\alpha$ where $A_p$ is the effective port area
$\alpha$ crank angle from exhaust port open

It should be noted that the geometric port area should be larger than the effective port area to allow for the coefficient of discharge.

SONIC FLOW THROUGH PORTS

For this case $u_t = a_t$

Equation (5) becomes

$$a_c^2 = \frac{\gamma+1}{2}a_t^2 \quad . \quad . \quad (14)$$

Equation (7) becomes

$$dW_c = -\phi A_c a_c \rho_c\left(\frac{2}{\gamma+1}\right)^{\frac{\gamma+1}{2(\gamma-1)}}\cdot dt \quad . \quad . \quad (15)$$

and equation (8) is

$$\frac{2}{\gamma-1}\left(\frac{\gamma+1}{2}\right)^{\frac{\gamma+1}{2(\gamma-1)}}\frac{da_c}{a_c^2} = -\frac{\phi}{L}\cdot dt \quad . \quad (16)$$

The left hand side can be integrated directly to give

$$\int\frac{\phi}{L}\cdot dt = \frac{2}{\gamma-1}\left(\frac{\gamma+1}{2}\right)^{\frac{\gamma+1}{2(\gamma-1)}}\left[\frac{1}{a_c}\right]_{a_{c1}}^{a_{c2}} \quad . \quad (17)$$

Introducing the parameter $x = \left(\frac{p_e}{p_c}\right)^{\frac{\gamma-1}{2\gamma}} = \frac{x_{cR}a_{cR}}{a_c}$

equation (17) becomes

$$\frac{x_{cR}a_{cR}}{L}\int\phi\cdot dt = \frac{2}{\gamma-1}\left(\frac{\gamma+1}{2}\right)^{\frac{\gamma+1}{2(\gamma-1)}}\left[x\right]_{x_{c1}}^{x_{c2}} \quad . \quad (18)$$

This expression applies to all values of $\gamma$. For the three values of $\gamma$ selected earlier, equation (18) in terms of $r$, $n$, $L$ and $T_{c1}$ is:

$\gamma = 1{\cdot}4$

$$\frac{\sqrt{T_{c1}}}{r_{c1}^{1/7}}\cdot\frac{1}{nL}\int\phi d\alpha = 1{\cdot}05725\left[r^{-1/7}\right]_{r_{c1}}^{r_{c2}} \quad (19)$$

$\gamma = 1{\cdot}333$

$$\frac{\sqrt{T_{c1}}}{r_{c1}^{1/8}}\cdot\frac{1}{nL}\int\phi d\alpha = 1{\cdot}29045\left[r^{-1/8}\right]_{r_{c1}}^{r_{c2}} \quad (20)$$

$\gamma = 1{\cdot}286$

$$\frac{\sqrt{T_{c1}}}{r_{c1}^{1/9}}\cdot\frac{1}{nL}\int\phi d\alpha = 1{\cdot}52485\left[r^{-1/9}\right]_{r_{c1}}^{r_{c2}} \quad (21)$$

the values of the critical pressure ratios $r_{cr}$ are

| | |
|---|---|
| $\gamma = 1{\cdot}4$ | $r_{cr} = 1{\cdot}89293$ |
| $\gamma = 1{\cdot}333$ | $r_{cr} = 1{\cdot}85262$ |
| $\gamma = 1{\cdot}286$ | $r_{cr} = 1{\cdot}82374$ |

SONIC AND SUBSONIC FLOW THROUGH PORTS

For this, the more general case, equations (10) and (18) are combined, the value of $x_{c1}$ in equation (10) and $x_{c2}$ in equation (18) corresponding to the critical pressure value.

In terms of pressure ratio $r$ and the other variables the following equations are obtained for this case.

$\gamma = 1{\cdot}4$

$$\frac{\sqrt{T_{c1}}}{nLr_{c1}^{1/7}}\int\phi d\alpha = 1{\cdot}1003 - 0{\cdot}03416\left[r_{c2}^{2/7}(1-r_{c2}^{-2/7})^{\frac{1}{2}}\times(2r_{c2}^{2/7}+3) + 6{\cdot}909\log_{10}\left(\tan\left(\frac{\theta}{2}+\frac{\pi}{4}\right)\right)\right] - 1{\cdot}0573\,r_{c1}^{-1/7} \quad . \quad . \quad . \quad (22)$$

$$r_{c1} > 1{\cdot}89293 > r_{c2}; \quad \cos\theta = r_{c2}^{-1/7}$$

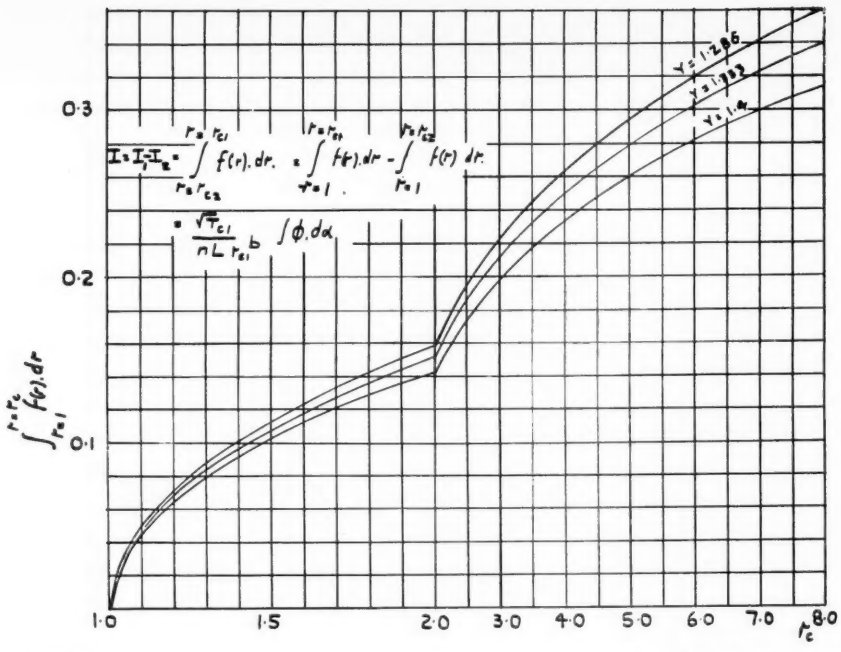


FIGURE 1.
Function $\int_{r=1}^{r=r_c} f(r).dr.$ against $r_c$.
Equations 22, 23, 24.

$$\gamma = 1{\cdot}333$$

$$\frac{\sqrt{T_{c1}}}{nLr_{c1}^{1/8}} \int \phi d\alpha = 1{\cdot}33478 - 0{\cdot}06143 \left[ (r_{c2}^{1/4} - 1)^{\frac{1}{2}} \times \right.$$
$$\left. \times \left( r_{c2}^{1/2} + \frac{4}{3} r_{c2}^{1/4} + \frac{8}{3} \right) \right] - 1{\cdot}29045\, r_{c1}^{-1/8} \qquad (23)$$
$$r_{c1} > 1{\cdot}85262 > r_{c2}$$

$$\gamma = 1{\cdot}284$$

$$\frac{\sqrt{T_{c1}}}{nLr_{c1}^{1/9}} \int \phi d\alpha = 1{\cdot}57026 - 0{\cdot}33784$$
$$\left[ \frac{1}{6} r_{c2}^{1/9} (r_{c2}^{2/9} - 1)^{\frac{1}{2}} \left( r_{c2}^{4/9} + \frac{5}{4} r_{c2}^{2/9} + \frac{15}{8} \right) + \right.$$
$$\left. + 0{\cdot}7197 \log_{10} \left( \tan \left( \frac{\theta}{2} + \frac{\pi}{4} \right) \right) \right] - 1{\cdot}52485\, r_{c1}^{-1/9} . \qquad (24)$$
$$r_{c1} > 1{\cdot}82374 > r_{c2}; \quad \cos\theta = r_{c2}^{-1/9}$$

The above expressions are somewhat cumbersome to manipulate. They have therefore been evaluated and plotted in the form of a function $\int_{r=1}^{r=r_c} f(r) \, . \, dr$ in Fig. 1. To obtain the numerical solution of the right hand side of equations (22-24) the difference between the values of the function for $r = r_{c1}$, and $r = r_{c2}$ is read directly from the graph.

To calculate the port area, let $I_1$ equal the numerical value for $r = r_{c1}$ and $I_2$ equal the numerical value for $r = r_{c2}$ then

$$\frac{\sqrt{T_{c1}}}{nLr_{c1}^{b}} \int_{\alpha_1}^{\alpha_2} \phi d\alpha \; (b = 1/7, 1/8, 1/9) = I_1 - I_2 \qquad (25)$$

Substitution of the speed ($n$) in r.p.m., cylinder length ($L$) in feet, release pressure ratio ($r_{c1}$) and temperature ($T_{c1}$) in equation (25) will give the requisite port area times crank angle characteristic from which the port dimensions can be determined. For any value of $\gamma$ between 1·286 and 1·4 linear interpolation may be used.

THE EFFECT OF $\gamma$ ON PORT AREA

In Fig. 2 the port area parameter $\frac{\sqrt{T_{c1}}}{nL} \int \phi d\alpha$ is plotted against release pressure $r_{c1}$ for $\gamma = 1{\cdot}4$, 1·333, 1·286 for a gas expanding from $r = r_{c1}$ to $r_{c2} = 1$.

It will be seen that the effect of a decrease in $\gamma$ is to increase the required port area. The increase is of the order of 3-4 per cent ($\gamma = 1{\cdot}4$ to 1·333) and 6-8 per cent for $\gamma = 1{\cdot}4$ to 1·286.

CONCLUSIONS

A method is developed for calculating the exhaust port area for various values of $\gamma$. It is shown that the effect of a decrease in $\gamma$ is to increase the required port area. A simple chart is given from which a rapid calculation of the port area may be obtained.

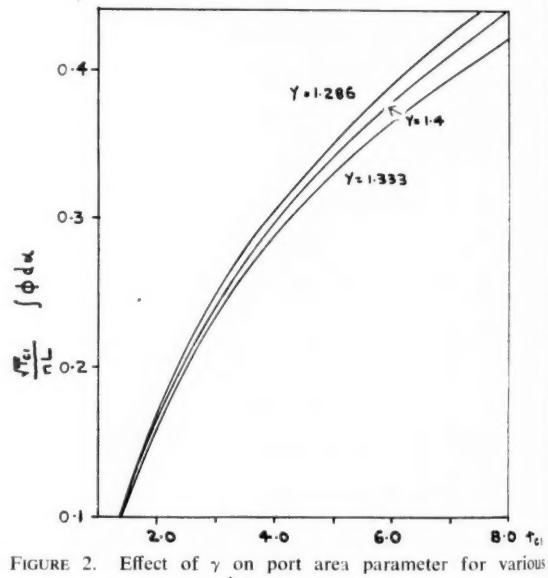


FIGURE 2. Effect of $\gamma$ on port area parameter for various release pressures.

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# *Determination of Effective End Fixity of Columns with Unequal Rotational End Restraints by Means of Vibration Test Data*

by

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THE determination of effective column end fixity by means of vibration testing has been established for the case when the rotational end restraints of the column are equal.[1] It is the purpose of the present work to present solutions for the general case.[2] The method of solution is straightforward. Results are listed in a convenient tabular array.

NOTATION

| | |
|---|---|
| $A$ | column cross-sectional area |
| $a, b, c, d$ / $\bar{a}, \bar{b}, \bar{c}, \bar{d}$ | deflected shape parameters |
| $C$ | effective column end fixity |
| $E$ | Young's modulus |
| $f_n$ | $n$th natural frequency, cycles/sec. |
| $f_{no}$ | $n$th natural frequency for a pinned end column |
| $I$ | moment of inertia of column cross section |
| $(kL)^2$ | parameter proportional to column natural frequency |
| $(\bar{k}L)^2$ | parameter proportional to effective column end fixity |
| $L$ | actual column length |
| $n$ | 1, 2 |
| $P$ | column buckling load |
| $x$ | axial co-ordinate |
| $y$ | lateral deflection |
| $y_b$ | buckling deflection |
| $y_v$ | vibration deflection |
| $y'$ | derivative with respect to $x$ |
| $\alpha, \beta$ | deflected shape parameters |
| $\rho$ | mass density of column |
| $\omega_n$ | natural frequency, radians/sec. |

METHOD OF SOLUTION

Column geometry is shown in Fig. 1. The basic differential equation defining the problem is

$$EIy_v'''' = y\omega_n^2 A\rho - Py'' \quad . \quad . \quad (1)$$

The problem is broken up into two parts:

(*i*) Buckling without vibration $\omega_n = 0$.
The general solution of equation (1) is in this case

$$y_b = \bar{a} + \frac{\bar{b}x}{L} + \bar{c}\cos \bar{k}x + \bar{d}\sin \bar{k}x \quad . \quad (2)$$

where $$\left(\frac{\bar{k}L}{\pi}\right)^2 = C = \frac{PL^2}{\pi^2 EI}; \quad 1 \leqslant C \leqslant 4 \quad . \quad (2a)$$

(*ii*) Vibration without end load $P = 0$.
The general solution of equation (1) is in this case

$$y_v = a\cosh kx + b\cos kx + c\sin kx + d\sinh kx$$

where $$\left(\frac{k_n L}{n\pi}\right)^2 = \frac{f_n}{f_{no}} = \sqrt{\left(\frac{\omega_n^2 A\rho L^4}{n^4\pi^4 EI}\right)} \quad . \quad (3a)$$

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and[3] $$\pi \leqslant k_1 L \leqslant 4{\cdot}730; \quad 2\pi \leqslant k_2 L \leqslant 7{\cdot}853$$

$$1 \leqslant \frac{f_1}{f_{10}} \leqslant 2{\cdot}26; \quad 1 \leqslant \frac{f_2}{f_{20}} \leqslant 1{\cdot}56 \quad . \quad (3b)$$

For each case it is necessary to satisfy two displacement boundary conditions, *i.e.* $y = 0$ at $x = 0$ and $x = L$. The deflection functions and their first two derivatives with respect to $x$ then become

*buckling:*

$$y_b = (1 - \cos \bar{k}x) - \frac{x}{L}(1 - \cos \bar{k}L) + \alpha\left[\left(-\frac{x}{L}\sin \bar{k}L + \sin \bar{k}L\right)\right] \quad (4a)$$

$$y_b' = \bar{k}\sin \bar{k}x - \left(\frac{1 - \cos \bar{k}L}{L}\right) + \alpha\left[\left(-\frac{\sin \bar{k}L}{L} + \bar{k}\cos \bar{k}x\right)\right] \quad . \quad . \quad . \quad (4b)$$

$$y_b'' = (\bar{k})^2(\cos \bar{k}x - \alpha \sin \bar{k}x) \quad . \quad . \quad . \quad . \quad (4c)$$

*vibration:*

$$y_v = \cosh kx - \cos kx - \left(\frac{\cosh kL - \cos kL}{\sin kL}\right)\sin kx + \beta\left(-\frac{\sinh kL}{\sin kL}\sin kx + \sinh kx\right) \quad (5a)$$

$$y_v' = k\left[\sinh kx + \sin kx - \left(\frac{\cosh kL - \cos kL}{\sin kL}\right)\cos kx\right] + \beta k\left(-\frac{\sinh kL}{\sin kL}\cosh kx + \cosh kx\right). \quad (5b)$$

$$y_v'' = k^2\left[\cosh kx + \cos kx + \left(\frac{\cosh kL - \cos kL}{\sin kL}\right)\sin kx\right] + \beta k^2\left(\frac{\sinh kL}{\sin kL}\sin kx + \sinh kx\right). \quad (5c)$$

Since the column has the same rotational end restraint for the two conditions, *i.e.* buckling and vibration, the following equations must be satisfied:

$$\left(\frac{y_b''}{y_b'}\right)_{x=0} = \left(\frac{y_v''}{y_v'}\right)_{x=0}; \quad \left(\frac{y_b''}{y_b'}\right)_{x=L} = \left(\frac{y_v''}{y_v'}\right)_{x=L} \quad (6)$$

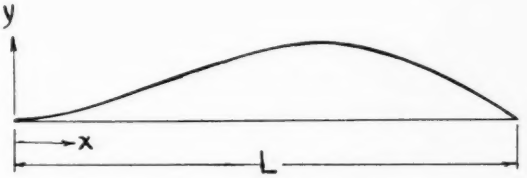


FIGURE 1. Column Geometry.

These equations are:

$$\frac{(\bar{k}L)^2}{-(1-\cos\bar{k}L)+\alpha(\bar{k}L-\sin\bar{k}L)} = \frac{2kL}{-\left(\frac{\cosh kL-\cos kL}{\sin kL}\right)+\beta\left(1-\frac{\sinh kL}{\sin kL}\right)} \quad . \quad (6a)$$

$$\frac{(\bar{k}L)^2(\cos\bar{k}L-\alpha\sin\bar{k}L)}{\bar{k}L\sin\bar{k}L-(1-\cos\bar{k}L)+\alpha(\bar{k}L\cos\bar{k}L-\sin\bar{k}L)} = \frac{2kL(\cosh kL+\beta\sinh kL)}{\sinh kL+\left(\frac{1-\cosh kL\cos kL}{\sin kL}\right)+\beta\left(\cosh kL-\frac{\sinh kL}{\sin kL}\cos kL\right)} \quad . \quad . \quad . \quad (6b)$$

Equations (6) hold for all modes of vibration. However only $n=1,2$ are required since values of two natural frequencies completely determine the effective column end fixity.

The unknowns in the problem at this stage are $\alpha$, $\beta_1$, $\beta_2$, and $\bar{k}L$; it is assumed that $k_1L$ and $k_2L$ are known having been determined by vibrating the column in its first two natural modes and measuring the corresponding frequencies.

The solution proceeds by eliminating $\beta$ in equations 6, *i.e.* solving equation (6*b*) for $\beta$ and substituting the result into equation (6*a*). A quadratic equation in $\alpha$ results. Since the buckled shape of the column is unique, the correct value of $\bar{k}L$ is the one for which the value of $\alpha$ is the same for equations involving $k_1L$ and $k_2L$. In order to determine such values, a series of values of $\bar{k}L$, $k_1L$, and $k_2L$ are assumed as follows:

$$\bar{k}L = 4{\cdot}1, 4{\cdot}2, 4{\cdot}3, \ldots, 5, 5{\cdot}1, 5{\cdot}2, 5{\cdot}3, \ldots, 6$$

$$k_1L = 3{\cdot}5, 3{\cdot}8, 4{\cdot}1, 4{\cdot}4; \quad k_2L = 6{\cdot}6, 6{\cdot}9, 7{\cdot}2, \text{and } 7{\cdot}5.$$

Then for each pair of values ($\bar{k}L$, $kL$), a pair of values of $\alpha$ are found from the quadratic equation mentioned before (imaginary values are discarded). Next curves are plotted of $\alpha$ against $\bar{k}L$ for constant values of $kL$. These curves are shown in Fig. 2. Wherever a curve for $k_1L$ crosses a curve for $k_2L$, a solution exists. For example, the curve for $k_1L=4{\cdot}4$ crosses the curve for $k_2L=7{\cdot}5$ at $\bar{k}L=5{\cdot}55$. A check on the calculations and plotting of Fig. 2 is obtained since the two curves must cross at two places for the same value of $\bar{k}L$ as shown. (Except in the very special case when there is a double root.)

TABLE I

VALUES OF $\bar{k}L$

| $k_1L$ | $k_2L$ = 6·6 | 6·9 | 7·2 | 7·5 |
|---|---|---|---|---|
| 4·4 | — | — | — | (5·76) 5·55 |
| 4·1 | — | — | (5·19) 4·93 | 4·6 |
| 3·92 | | (4·79) | 4·48 | |
| 3·8 | — | (4·54) 4·1 | 4·0 | 3·9 |
| 3·5 | (3·89) — | | | |
| | 6·49 6·6 | 6·72 6·9 | 7·0 7·2 | 7·35 7·5 |

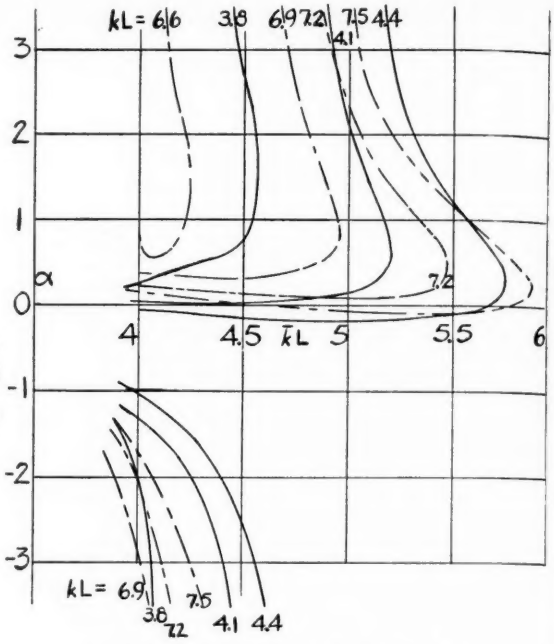


FIGURE 2. Curves of constant values of $kL$.

## RESULTS

Table I lists all available solutions obtainable from Fig. 2. Wherever a dash line appears, no solution is possible, *i.e.* it is impossible for a column to have such a pair of natural frequencies. It is interesting to note that the values adjacent to the dash lines represent columns whose rotational end restraints are approaching equality. The values of $\bar{k}L$ for such cases are listed in parentheses. These values were obtained from previously calculated data. Also given is the value for a column with one end pinned and one end fixed for which $k_1L=3{\cdot}92$ and $k_2L=7{\cdot}06$. By carrying out additional calculations according to the method of the present paper, more values may be obtained to give a more complete picture especially for $k_1L<3{\cdot}8$.

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# *A Matrix Method for the Numerical Solution of Linear Differential Equations with Variable Coefficients*

by

E. A. WINN

(*Blackburn and General Aircraft Ltd.*)

A METHOD of solution of linear differential equations is derived which requires no special starting procedure, and which is, in principle at least, capable of extension to any order of accuracy. Further advantages of the method are that boundary conditions are easy to satisfy, and that the solution of families of equations differing only in the input function requires little extra computation. The method requires the reciprocation of a matrix of order equal to the number of points for which a solution is to be obtained, but this can be much simplified by suitably partitioning the matrix, and with most automatic high-speed computers the reciprocation of a matrix is in any case an easily programmed operation.

Finite difference techniques are used throughout.

Although the method is here presented for, and applied to, equations of the second order, the extension to other orders is immediate.

NOTATION

| | |
|---|---|
| $a, b, c \ldots$ | coefficients of the differential equation |
| $f(x)$ | input function of the differential equation |
| $h$ | interval length |
| $n+1$ | number of stations for which a solution is required |
| $x$ | independent variable |
| $x_i$ | value of the independent variable at the $i^{\text{th}}$ station in the finite difference solution, *i.e.* $x_i = x_0 + ih$ |
| $y$ | dependent variable |
| $y_i$ | value of the dependent variable for $x = x_i$ |
| $[A]$, $\{B\}$, $\{C\}$ | matrices introduced in the text |
| $[Q]$ | integrating matrix |
| $\{U\}$ | a column matrix consisting entirely of units |

Brackets enclosing matrices denote their type, thus:—

| | |
|---|---|
| [ ] | denotes a square matrix |
| [ ] | denotes a diagonal matrix |
| { } | denotes a column matrix |
| [ ] | denotes a row matrix |

Primes denote differentiation with respect to the independent variable

Suffices denote the value at one of the stations, *e.g.* $a_i$ denotes the value of $a(x)$ for $x = x_i$

THEORY OF THE METHOD

The method is based upon an integrating matrix. This is defined as a matrix $[Q]$ such that

$$\begin{Bmatrix} y_0 - y_0 \\ y_1 - y_0 \\ \cdot \\ \cdot \\ \cdot \\ y_i - y_0 \\ \cdot \\ \cdot \\ \cdot \\ y_n - y_0 \end{Bmatrix} = [Q] \begin{Bmatrix} y_0' \\ y_1' \\ \cdot \\ \cdot \\ \cdot \\ y_0' \\ \cdot \\ \cdot \\ \cdot \\ y_n' \end{Bmatrix}$$

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Such a matrix can readily be constructed to any prescribed order of accuracy by the use of integrating formulae such as those to be found in Ref. 1.

For example, suppose that it is decided that errors of order $h^5 y^{(5)}$ can be accepted, then, to the given limits of error

$$y_1 - y_0 = \frac{h}{24}(9y_0' + 19y_1' - 5y_2' + y_3')$$

$$y_2 - y_0 = \frac{h}{3}(y_0' + 4y_1' + y_2' + 0)$$

$$y_3 - y_0 = \frac{3}{8}h(y_0' + 3y_1' + 3y_2' + y_3')$$

$$y_4 - y_0 = (y_4 - y_2) + (y_2 - y_0)$$

$$= \frac{h}{3}(y_0' + 4y_1' + 2y_2' + 4y_3' + y_4')$$

$$y_5 - y_0 = (y_5 - y_3) + (y_3 - y_0)$$

$$= \frac{h}{24}(9y_0' + 27y_1' + 27y_2' + 17y_3' + 32y_4' + 8y_5')$$

$$y_6 - y_0 = (y_6 - y_4) + (y_4 - y_2) + (y_2 - y_0)$$

and so on.

These equations can be written in matrix form as

$$\begin{Bmatrix} y_0 - y_0 \\ y_1 - y_0 \\ y_2 - y_0 \\ y_3 - y_0 \\ y_4 - y_0 \\ y_5 - y_0 \\ y_6 - y_0 \end{Bmatrix} = \frac{h}{24} \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 9 & 19 & -5 & 1 & 0 & 0 & 0 \\ 8 & 32 & 8 & 0 & 0 & 0 & 0 \\ 9 & 27 & 27 & 9 & 0 & 0 & 0 \\ 8 & 32 & 16 & 32 & 8 & 0 & 0 \\ 9 & 27 & 27 & 17 & 32 & 8 & 0 \\ 8 & 32 & 16 & 32 & 16 & 32 & 8 \end{bmatrix} \begin{Bmatrix} y_0' \\ y_1' \\ y_2' \\ y_3' \\ y_4' \\ y_5' \\ y_6' \end{Bmatrix}$$

or $$\{y_i\} - y_0\{U\} = [Q] \cdot \{y_i'\} \quad . \quad . \quad (1)$$

Suppose now that we require to solve an equation of the form

$$a(x) \cdot y'' + b(x) \cdot y' + c(x) \cdot y = f(x).$$

At a point $x_i$ we replace this with

$$a_i y_i'' + b_i y_i' + c_i y_i = f_i \quad . \quad . \quad . \quad (2)$$

This and the similar statements for $x_0$ to $x_n$ may be written

$$[a_i]\{y_i''\} + [b_i]\{y_i'\} + [c_i]\{y_i\} = \{f_i\} \quad . \quad (2a)$$

Now from (1) $$\{y_i\} = [Q]\{y_i'\} + y_0\{U\} \quad . \quad . \quad (1a)$$

and similarly $$\{y_i'\} = [Q]\{y_i''\} + y_0'\{U\} \quad . \quad . \quad (3)$$

whence $$\{y_i\} = [Q]^2\{y_i''\} + y_0'[Q]\{U\} + y_0\{U\} \quad . \quad (4)$$

Substituting (3) and (4) in (2*a*),

$$([c_i][Q]^2 + [b_i][Q] + [a_i])\{y_i''\} + y_0'([c_i][Q] + [b_i])\{U\} + y_0[c_i]\{U\} = \{f_i\} \quad . \quad . \quad . \quad (5)$$

which is written as

$$[A]\{y_i''\}+\{B\}\,y_0'+\{C\}\,y_0=\{f_i\}.$$

Then

$$\{y_i''\}=[A]^{-1}\{f_i\}-y_0'[A]^{-1}\{B\}-y_0[A]^{-1}\{C\} \quad . \qquad (6)$$

and by applying (3) and (4) to (6)

$$\{y_i'\}=[Q][A]^{-1}\{f_i\}+$$
$$+y_0'\left([Q]\{U\}-[Q]^2[A]^{-1}\{B\}\right)-$$
$$-y_0[Q][A]^{-1}\{C\},$$
$$\{y_i\}=[Q]^2[A]^{-1}\{f_i\}+$$
$$+y_0'\left([Q]\{U\}-[Q]^2[A]^{-1}\{B\}\right)+$$
$$+y_0\left(\{U\}-[Q]^2[A]^{-1}\{C\}\right).$$

It will be seen that the solution is obtained in the form of a particular integral and two complementary functions. Since the values of these functions and of their derivatives is known, the values of $y_0$ and $y_0'$ can easily be found which will satisfy almost any boundary conditions.

EXAMPLE

The following equation is solved as an example: $y''+xy'+y=2x$ in the range $0\leqslant x\leqslant 0{\cdot}5$ using an interval of 0·1.

The integrating matrix $[Q]$ will be constructed from the six-point formulae of Ref. 1.

$$[Q]=\frac{0{\cdot}1}{1440}\begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0\\ 493 & 1337 & -618 & 302 & -83 & 9\\ 448 & 2064 & 224 & 224 & -96 & 16\\ 459 & 1971 & 1026 & 1026 & -189 & 27\\ 448 & 2048 & 768 & 2048 & 448 & 0\\ 475 & 1875 & 1250 & 1250 & 1875 & 475 \end{bmatrix}$$

$$\lceil a_i\rfloor=\lceil c_i\rfloor=I \text{ (the unit matrix)}$$

$$\lceil b_i\rfloor=\lceil 0 \quad 0{\cdot}1 \quad 0{\cdot}2 \quad 0{\cdot}3 \quad 0{\cdot}4 \quad 0{\cdot}5\rfloor$$

$$\{f_i\}=\{0 \quad 0{\cdot}2 \quad 0{\cdot}4 \quad 0{\cdot}6 \quad 0{\cdot}8 \quad 1{\cdot}0\}$$

$$\lceil c_i\rfloor[Q]+\lceil b_i\rfloor$$
$$=\begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0\\ 0{\cdot}0342 & 0{\cdot}1928 & -0{\cdot}0429 & 0{\cdot}0210 & -0{\cdot}0058 & 0{\cdot}0006\\ 0{\cdot}0311 & 0{\cdot}1433 & 0{\cdot}2156 & 0{\cdot}0156 & -0{\cdot}0067 & 0{\cdot}0011\\ 0{\cdot}0319 & 0{\cdot}1369 & 0{\cdot}0712 & 0{\cdot}3713 & -0{\cdot}0131 & 0{\cdot}0019\\ 0{\cdot}0311 & 0{\cdot}1422 & 0{\cdot}0533 & 0{\cdot}1422 & 0{\cdot}4311 & 0{\cdot}0000\\ 0{\cdot}0330 & 0{\cdot}1302 & 0{\cdot}0868 & 0{\cdot}0868 & 0{\cdot}1302 & 0{\cdot}5330 \end{bmatrix}$$

$$(\lceil c_i\rfloor[Q]+\lceil b_i\rfloor)[Q]+\lceil a_i\rfloor=[A]$$
$$=\begin{bmatrix} 1{\cdot}0000 & 0{\cdot}0 & 0{\cdot}0 & 0{\cdot}0 & 0{\cdot}0 & 0{\cdot}0\\ 0{\cdot}0058 & 1{\cdot}0139 & -0{\cdot}0077 & 0{\cdot}0041 & -0{\cdot}0012 & 0{\cdot}0001\\ 0{\cdot}0119 & 0{\cdot}0455 & 0{\cdot}9981 & 0{\cdot}0066 & -0{\cdot}0025 & 0{\cdot}0004\\ 0{\cdot}0184 & 0{\cdot}0721 & 0{\cdot}0211 & 1{\cdot}0287 & -0{\cdot}0063 & 0{\cdot}0009\\ 0{\cdot}0245 & 0{\cdot}1016 & 0{\cdot}0279 & 0{\cdot}0753 & 1{\cdot}0104 & 0{\cdot}0004\\ 0{\cdot}0316 & 0{\cdot}1243 & 0{\cdot}0552 & 0{\cdot}0751 & 0{\cdot}0710 & 1{\cdot}0179 \end{bmatrix}$$

Then after inverting the matrix we have

$$[A]^{-1}=$$
$$\begin{bmatrix} 1{\cdot}0000 & 0{\cdot}0 & 0{\cdot}0 & 0{\cdot}0 & 0{\cdot}0 & 0{\cdot}0\\ -0{\cdot}0057 & 0{\cdot}9861 & 0{\cdot}0077 & -0{\cdot}0041 & 0{\cdot}0012 & -0{\cdot}0001\\ -0{\cdot}0116 & -0{\cdot}0447 & 1{\cdot}0017 & -0{\cdot}0064 & 0{\cdot}0024 & -0{\cdot}0004\\ -0{\cdot}0173 & -0{\cdot}0687 & -0{\cdot}0212 & 0{\cdot}9721 & 0{\cdot}0060 & -0{\cdot}0009\\ -0{\cdot}0220 & -0{\cdot}0928 & -0{\cdot}0268 & -0{\cdot}0718 & 0{\cdot}9891 & -0{\cdot}0003\\ -0{\cdot}0269 & -0{\cdot}1065 & -0{\cdot}0518 & -0{\cdot}0658 & -0{\cdot}0697 & 0{\cdot}9825 \end{bmatrix}$$

$$\{B\}=(\lceil c_i\rfloor[Q]+\lceil b_i\rfloor)\{U\}$$
$$=\{0{\cdot}0 \quad 0{\cdot}2 \quad 0{\cdot}4 \quad 0{\cdot}6 \quad 0{\cdot}8 \quad 1{\cdot}0\}$$
$$\{C\}=\lceil c_i\rfloor\{U\}$$
$$=\{U\}.$$

Hence

$$\{y_i''\}=\begin{Bmatrix} 0{\cdot}0\\ 0{\cdot}19867\\ 0{\cdot}38946\\ 0{\cdot}56496\\ 0{\cdot}71864\\ 0{\cdot}84526 \end{Bmatrix}-y_0'\begin{Bmatrix} 0{\cdot}0\\ 0{\cdot}19867\\ 0{\cdot}38946\\ 0{\cdot}56496\\ 0{\cdot}71864\\ 0{\cdot}84526 \end{Bmatrix}-y_0\begin{Bmatrix} 1{\cdot}00000\\ 0{\cdot}99501\\ 0{\cdot}98020\\ 0{\cdot}95600\\ 0{\cdot}92312\\ 0{\cdot}88250 \end{Bmatrix}$$

$$\{y_i'\}=\begin{Bmatrix} 0{\cdot}0\\ 0{\cdot}00997\\ 0{\cdot}03947\\ 0{\cdot}08735\\ 0{\cdot}15173\\ 0{\cdot}23017 \end{Bmatrix}+y_0'\begin{Bmatrix} 1{\cdot}00000\\ 0{\cdot}99003\\ 0{\cdot}96053\\ 0{\cdot}91265\\ 0{\cdot}84827\\ 0{\cdot}76983 \end{Bmatrix}-y_0\begin{Bmatrix} 0{\cdot}00000\\ 0{\cdot}09950\\ 0{\cdot}19604\\ 0{\cdot}28680\\ 0{\cdot}36925\\ 0{\cdot}44125 \end{Bmatrix}$$

$$\{y_i\}=\begin{Bmatrix} 0{\cdot}0\\ 0{\cdot}00033\\ 0{\cdot}00265\\ 0{\cdot}00884\\ 0{\cdot}02067\\ 0{\cdot}03966 \end{Bmatrix}+y_0'\begin{Bmatrix} 0{\cdot}0\\ 0{\cdot}09967\\ 0{\cdot}19735\\ 0{\cdot}29116\\ 0{\cdot}37933\\ 0{\cdot}46034 \end{Bmatrix}+y_0\begin{Bmatrix} 1{\cdot}00000\\ 0{\cdot}99501\\ 0{\cdot}98020\\ 0{\cdot}95600\\ 0{\cdot}92312\\ 0{\cdot}88250 \end{Bmatrix}$$

Suppose that the boundary conditions are

$$y'(0{\cdot}2)=y'(0{\cdot}3) \quad \text{and} \quad y(0{\cdot}4)=1{\cdot}0$$

then we have

$$0{\cdot}03947+0{\cdot}96053\,y_0'-0{\cdot}19604\,y_0=0{\cdot}08735+$$
$$+0{\cdot}91265\,y_0'-0{\cdot}28680\,y_0$$

and

$$0{\cdot}02067+0{\cdot}37933\,y_0'+0{\cdot}92312\,y_0=1{\cdot}0.$$

By solving these equations it is found that

$$y_0=2{\cdot}9402 \qquad y_0'=-4{\cdot}5733.$$

Whence

$$\{y_i\}=\begin{Bmatrix} 2{\cdot}940\\ 2{\cdot}470\\ 1{\cdot}982\\ 1{\cdot}488\\ 1{\cdot}000\\ 0{\cdot}529 \end{Bmatrix} \qquad \{y_i'\}=\begin{Bmatrix} -4{\cdot}573\\ -4{\cdot}810\\ -4{\cdot}930\\ -4{\cdot}930\\ -4{\cdot}813\\ -4{\cdot}588 \end{Bmatrix}$$

These figures have been rounded from calculations originally carried to seven places, and the results then obtained agreed to within 2 in the 7th place with the series solution of the equation.

DEVELOPMENTS

Although the method has here been derived and presented for a second-order differential equation, the extension to other orders is immediate. Further, the extension to simultaneous equations should be straightforward, perhaps using partitioned matrices.

ACKNOWLEDGMENTS

The author wishes to thank Blackburn and General Aircraft Ltd. for their permission to publish this note, and Professor A. R. Collar, of the University of Bristol, and G. R. Walsh and A. M. H. Dunn for their helpful comments on the presentation of this paper.

REFERENCE

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# Graduates' and Students' Section

FOLLOWING on our recent correspondence on the use and misuse of the young engineer, we have received a lengthy letter concerned with engineer wastage caused by National Service requirements. Extracts from this letter are given below:—

Dear Sir,

After reading the request for replies to correspondence on the subject of young engineers, I feel that I must write on a certain subject which has not been openly mentioned before. I refer of course to National Service.

Two great men, Sir Roy Fedden and Sir Edward Appleton, have repeatedly stated that there are not enough engineers, technicians and scientists of all grades, and because of this our economy, as a nation, is in great danger. Two men against the mind of officialdom are useless, it requires the whole of the industry led by the Society, the S.B.A.C. and the other associated professional bodies to tell the Government and Ministry of Labour that we cannot survive economically unless the young engineer and technician is free from "call-up". You may well ask "What is two years?", but in an industry such as ours, especially where research and development are concerned, two years in the forces means a loss of often as much as four equivalent years.

Service Chiefs claim that the forces need technicians just as much as industry, but what service chiefs mean by technicians are what we in industry know as skilled and semi-skilled PRODUCTION fitters and machine tool operators. The type of person who would be called a technician in industry is an aerodynamicist, chemist, computer specialist, design draughtsman, development engineer, mathematician, metallurgist, performance technician, physicist, stress man or weight engineer, and it is this type of man who is being unnecessarily "called-up".

It is possible to meet potential members of the American aircraft industry among National Servicemen. Many young engineers are rapidly becoming cynical about the talk of an all-out drive to recruit more engineers and technicians, when they idle their time away dressed in sack cloth and sweeping up ashes. It is felt that, due to the present "system", the young man entering engineering in one of its many branches, spending at least five years engrossed in an intensive study of both theoretical and practical aspects of his profession, is heavily penalised in status, let alone financially, finding that very little, if any, notice is taken of his pre-service experience and qualifications. On top of this, he sees the young man of 18 (who left school at 15, with nothing to his credit and idled his time away) signing on as a regular, being given many advantages and opportunities of rapid promotion based only on service training.

Last year, Lord Templewood publicly stated: "The present system of short term National Service is not suited to a technical service such as the R.A.F. Recruits are trained at great expense and at the end of their two years' service are still largely inexperienced. Each man probably costs the country £5,000. Could there be a more wasteful and extravagant way of providing technicians?"

Three considerations arise from these remarks: firstly continued "call-up" of trained, qualified, professional engineers—immediate deficit of £5,000 per man with very slow long term recovery. Secondly, professional engineers leaving the country to avoid "call-up" causes a long term loss progressively increasing. Thirdly, the cessation of "call-up" of the professional engineer—immediate saving of £5,000 plus a long term increase at improving value.

The idea of progressively raising the call-up age serves no useful purpose at all.

The writing is plainly written on the wall and it does not require any David to interpret it. If nothing is done to improve the present position of the young engineer and technician, we will no longer be able to claim leadership in anything, since if current reports are true, America and Russia as well as others, are ahead of us on airframes, and equal on engines. We need to put our trained manpower to its fullest economic use and not deliberately waste it.

Air Cdre. Banks has recently given a warning which should not be ignored and, again to quote Sir Roy Fedden, ". . . the number of aeronautical engineers graduating in one recent year in Britain was 60, in the U.S.A. 1,000 and in Russia 2,500."

Now is the time for the society to do something about this problem. Along with the industry it should tackle the Minister of Labour, or the future of the industry is surely doomed.

Yours faithfully,
A. T. Hills.

We would like to hear the views of others on this problem, particularly those of the upper realms of the R.A.F.—A.D.B.

## N. E. Rowe Lectures

ON the evening of 15th January two lectures were given before section members at 4 Hamilton Place to decide the senior winner of the N. E. Rowe Medal Competition for this year. Medals are awarded for the best papers given by Branch members aged under 21 and between 21 and 26.

The lectures were "Fins", by J. Wolkovitch of the Southampton Branch, and "Possible Flight Paths for Helicopters" by P. F. Sutherby of the Bristol Branch. They were judged by the President, Mr. E. T. Jones, the Chairman of the Branches Committee, Mr. Handel Davies, Mr. N. E. Rowe, who inaugurated the competition and after whom it is named, and two other Council members, Mr. B. S. Shenstone and Air Marshal Sir Owen Jones.

Each of the lecturers spoke for 20 minutes and was then questioned about his paper for a similar length of time. At the end of the evening voting papers were collected and Mr. Sutherby was declared the winner.

Mr. Wolkovitch opened his talk on Fins by describing their design requirements. He showed how fin area depends on the need for adequate weather-cock stability and lateral response with a well-damped oscillatory mode. He showed also how side-slip angle decides fin area.

Speaking of modern developments he indicated that inertial cross-coupling in roll is becoming an increasing problem with the latest aircraft configurations; the critical rate of roll is becoming lower than that which can be reached in flight. He suggested that fins should be large enough to ensure a critical rate of roll not less than 200°/sec.

In his lecture—"Possible Flight Paths for Helicopters"—Mr. Sutherby spoke of the advantages that could be gained if helicopters operated at altitudes higher than the 1,000-2,000 ft common today.

He based his lecture on consideration of a helicopter suitable for commercial operations. Large, by current standards, it would be powered by free-turbine engines and able to hover outside the ground cushion with one dead engine. A helicopter of this type would have much surplus power and would show economic advantages if operated at altitude.

Operational altitude of such helicopters would be limited by stage distance—8,000 ft was suggested for a 100-mile stage.

The lecturer foresaw the need for two types of helicopter, a simple type cruising at heights up to 6,000 ft for ranges up to 100 miles and for longer stages a more advanced pressurised helicopter, with a fixed lifting surface. It would operate on stages from 100-300 miles at altitudes of 12,000 to 15,000 ft. —J.R.C.

## Visits

### Southern Air Traffic Control Centre.

A VISIT has been arranged for Saturday morning of the 16th February, 1957, to the Southern Air Traffic Control Centre at Harmondsworth, near London Airport. It is from here that they direct the airliners through the upstairs traffic jam and get them in and out of London Airport. The centre is on the Bath Road, and easily accessible by bus and Green Line.

Since this notice will appear very near the date of the visit, people interested should contact the Hon. Visits Secretary at once, either by writing to Mr. N. K. Benson, 14 Wakering Road, Barking, Essex (telephone RIPpleway 3923) or telephoning during office hours GLAdstone 8000 (Technical Office).

At the time of writing, the Lotus visit has not taken place, but will be reported in the March Journal. For the future, we have practically fixed visits to airframe and engine companies in the London area for late March and April. We have also been offered a visit to the R.A.F. Rocket Propulsion Department at Westcott, Bucks., but this visit cannot be contemplated until the petrol situation is easier.—N.K.B.

# THE LIBRARY
## *Reviews*

WING THEORY. *A. Robinson and J. A. Laurmann. Cambridge Aeronautical Series. Cambridge University Press, 1956. 569 pp. Diagrams. 75s.*

The authors of this valuable book have neatly spiked the guns of potential critics by stating at the outset—and in an ancient language!—that, in all great enterprises, it is difficult to please everyone. Certainly in this book, many people will fail to find their own favourite topics embraced by the extremely wide title of Wing Theory; equally very many other people will be delighted to possess, within the same two covers, such a wide diversity of material about the theoretical aspects of fluid flow past lifting surfaces.

It is important to stress that this is an almost purely theoretical account of potential flow; there is hardly any consideration of the effects of viscosity and the boundary layer, or of the validity of the potential approximation. As a result the book will be primarily used by mathematicians who do not care to admit to unpleasant physical facts, and by teachers and their post-graduate students. To the latter especially, the work will be of the greatest value; it is by far the most comprehensive account of potential theory so far published in a single volume and the gaps it leaves will readily be filled in by any experienced teacher.

Five large Chapters form the book; each could have been more drastically sub-divided for easier reading. The first two—Foundations, and Aerofoil Theory for Steady Flow in Two Dimensions—follow conventional lines, although one notices that much important post-war work has been omitted in the latter. Aerofoil Theory for Steady Flow in Three Dimensions, the third chapter, is a well-balanced account of the various linearised theories. The book breaks new and exciting ground in the inclusion of the last two chapters, on Aerofoils in Compressible Flow, and Theory of Aerofoils in Unsteady Motion. Naturally the authors have had to be highly selective in their choice of material for both these Chapters but what they have decided to retain forms an excellent basis both for teachers and research workers.

It is a very great achievement for the authors to have produced this book, and aeronautical literature is enriched by its appearance. It can warmly be recommended to all libraries; for the individual it is a more personal matter, and both the style and the content of the book must commend themselves to the individual before he finds the price of the book in his pocket.—BRYAN THWAITES.

HIGH SPEED AERODYNAMICS AND JET PROPULSION, VOLUME II. COMBUSTION PROCESSES. *Edited by Bernard Lewis, Robert N. Pease and Hugh S. Taylor. Oxford University Press, London, 1956. 662 pp. 84s.*

The object of this series is given in the Preface as a comprehensive treatment of fundamental aspects of aerodynamics and propulsion problems of high speed flight together with a survey of relevant aspects of the basic science. Volume II on Combustion Processes consists of six parts containing fifteen articles compiled by a total of nineteen authors. Limited to four hundred words the reviewer can attempt little more than to summarise the subjects covered by these authors.

The range and treatment of the selected subjects suggest that the volume was intended for the post-graduate student rather than for the specialist. The method of presentation is likely to be more familiar to the physical chemist than to the engineer. The articles appear to have been completed in 1953 or 1954 and contain selected references to the research literature up to those dates together with, in some instances, bibliographies for further study. The space allocated to individual topics is too small for their treatment to be comprehensive and it is natural that, in some articles, the views and work of the respective authors should predominate. However, where divergent theories or interpretations exist they are referred to, if not adequately reviewed.

Part 1. Thermodynamics of Combustion is edited by Bernard Lewis and contains three sections. The first two, A. High Temperature Equilibrium, and B. Expansion Processes, are written by J. M. Carter and David Altman and deal in a simple manner with the calculation of equilibrium chemical composition, flame temperature and the thermodynamic properties of combustion gases under static and flow conditions. Section C. Computational Methods in Combustion Calculations by S. R. Brinkley, Junior, deals with generalised computational methods for thermodynamic properties at chemical equilibrium.

Part 2. Chemical Kinetics of Combustion, edited by H. S. Taylor, contains Section D. Fundamentals of Chemical Kinetics, an introduction to the elementary theory of chemical kinetics by that author, which concludes with a brief discussion of the problem of extending the concepts of classical chemical kinetics to the rates of reactions in flames. Section E. Kinetics of Several Oxidation Reactions by R. N. Pease, reviews, in some detail, the state of present knowledge in the slow reaction and explosion limits of hydrogen, carbon monoxide and hydrocarbons with oxygen. Part 3. Flame Propagation in Gases, edited by Bernard Lewis, begins with Section F. Mechanics of Reacting Continua by J. M. Richardson and S. R. Brinkley which, as an introduction to the statement of the problem of flow systems involving chemical reaction, makes no concession to the interests or experience of the average student. Section G. Combustion Waves in Non-turbulent Gases by Bernard Lewis and G. von Elbe is a condensed version of the chapter in the authors' well known book published in 1951. It is a pity that, for the purposes of this volume, they were not able to clarify their discussion of the relation between the stability of combustion waves and the spatial variation of total enthalpy. The treatment of limits of inflammability is made obscure by the use of average reaction rates and reaction zone widths and is not, in the reviewer's opinion, a convincing demonstration of the prediction of limits in the absence of energy losses. The two following sections give accounts of theory and experimental data on turbulent premixed flames by Béla Karlovitz and on diffusion flames by K. Wohl and C. W. Shipman.

Part 4, edited by R. N. Pease, deals with the combustion of liquid and solid fuels in four sections: J. Liquid Fuels by J. P. Longwell, K. Solid Fuels by M. Gerstein and K. P. Coffin, L. Liquid Propellants by David Altman and S. S. Penmer, and M. Solid Propellants by Clayton Hugget. In the main these subjects require a technological rather than an academic approach; as is remarked by the authors of one section, the application of combustion to propulsion is at present more of an art than science. Since one would

expect the state of knowledge and the amount of published information on these subjects to be changing rapidly, it would have been more convenient had Parts 4 and 5 been published separately from Parts 1, 2 and 3 whose subject matter should require less frequent revision. One curious omission from the liquid propellant section is the subject of combustion instability; presumably this will be treated in a later volume. Section M contains an excellent introduction to the combustion of solid propellants, and implies that solid propellant motor design will be covered by Volume XII.

Volume II ends with two short articles, one on detonation processes by A. R. Ubbelohde and J. Copp, and the other on energy production in nuclear reactions by H. Soodak. Although the editors have clearly taken great pains to introduce some unity of presentation and to avoid duplication by cross-referencing, the volume as a whole suffers from the attempt to cover too much ground in too little space and from the lack of a uniform standard of discrimination in the selection and presentation of material. Although the authors are clearly experts in their particular fields they are not all expert in imparting their knowledge in a clear and easily readable style. The result is informative but not always illuminating.

The subject index is adequate and the typography immaculate.—G. K. ADAMS.

ELEMENTARY DIFFERENTIAL EQUATIONS. *W. T. Martin and E. Reissner. Addison-Wesley, Cambridge 42, Massachusetts, U.S.A., 1956. 260 pp. $5.50.*

This book on differential equations has been written as an introduction to the subject for students of science and engineering. It begins with a chapter on geometrical and physical problems which is intended to demonstrate the translation of problems from the fields of science and engineering into mathematical equation form. This it does admirably. The second chapter deals with the first order equation. General, particular and singular solutions are discussed and solution in power series of linear and non-linear problems. Chapter 3 deals with the second order equation and here stress is put on the linear equation. Equations with constant coefficients are treated and the method of variation of parameters is introduced. Power series methods are again discussed. Chapter 4 is on the $n^{th}$ order equation. The Laplace transform method for the initial value problem of the $n^{th}$ order equation with constant coefficients is demonstrated. Chapter 5 is the final chapter on ordinary differential equations and in it systems of simultaneous first order equations are discussed. Systems with constant coefficients are treated in the traditional way and also by means of the Laplace transform. No attempt has been made to introduce the reader to operational methods when dealing with equations with constant coefficients.

Chapter 6 begins with a treatment of the problem of finding numerical values for the solution of a differential equation. Applications are given of the trapezoidal rule and of Simpson's rule to the step-by-step solution of first order equations. This leads to solution by iteration and from there to Picard's method. Chapter 7 contains a brief treatment of finite difference equations. The analytical solutions of certain types of difference equations are given, but no attempt is made to relate the work to practical finite-difference methods for numerical computation. A notable absence is the omission of any mention of Runge-Kutta type formula for numerical integration. Chapter 8 is devoted to a short introduction to the subject of partial differential equations. Second order equations are treated by the method of separation of variables. Fourier series are touched on and other orthogonal functions are mentioned.

In the preface the authors say that " one of our main aims has been to establish a number of fundamental notions rather firmly in the readers' mind, by considering them not just once but by returning to them on several occasions each time in a slightly different context." This is brought out by their treatment of the power series method which is mentioned in four chapters. Each extension of the method is discussed separately. In this way the idea is emphasised and the reader is brought to realise the importance of the method. However it means that the various results of the power series method are scattered throughout the text.

The style is very readable, but in some places the lack of formal statements and summary of results is felt. The book has a liberal number of worked examples and exercises with answers. The price of $5.50 is rather high for sterling area readers.—H. H. ROBERTSON.

ELASTICITY, FRACTURE AND FLOW. *J. C. Jaeger. Methuen's Monographs on Physical Subjects. Methuen, London, 1956. 150 pp. 10s. 6d.*

This monograph has been written to provide a fairly full elementary account of the basic mathematics of the theories of elasticity, plasticity, viscosity and rheology. While it may be regarded as an introduction to the larger works on these various subjects, this book gives an introduction with a difference—and an important one at that. For considerable space is devoted to a rather general account of the behaviour of materials and the nature of the appropriate idealisations of theoretical analysis is explained in the light of them.

There are three chapters, of which the first deals with stress and strain. The second chapter concerns the mechanical behaviour of actual materials and introduces theories of failure, yield criteria and associated topics. The last chapter covers equations of motion and equilibrium and is illustrated by a number of solutions to special problems.

Although this is essentially an elementary book, it requires a good deal of effort on the part of its readers. It is fairly short (150 pp.) and covers much ground. It can be recommended as giving a lucid introduction to the mechanics of deformable solids.—R. E. D. BISHOP.

ELECTRONICS AND ELECTRON DEVICES. *A. L. Albert. Macmillan, New York, 1956. 582 pp. Illustrated. 44s.*

This is an American text book written by the Professor of Communication Engineering at the Oregon State College for use by his undergraduates. It forms the third edition of a book " Fundamental Electronics and Vacuum Tubes " first published in 1938 and well known in this country. The present edition with a different title is almost completely rewritten. It contains seventeen chapters and almost six hundred pages. The price of two guineas is very competitive for this size of work.

There is an adequate index, and at the end of each chapter a large bibliography which is almost exclusively American and a set of numerical problems. In addition, the author has given separately a set of fundamental questions from which the reader, by going through these after finishing a chapter, can immediately tell whether or not he has grasped the important points of the chapter.

The first chapter on " basic electronic theory " is built round the classical picture of an electron as a charged particle and the Bohr atom. A simple descriptive picture

of solid state physics is included, terminating with the movement of charges in semi-conductors. The main body of the book follows the well-known pattern of so many electronics books dealing, by chapter, with diodes, triodes, pentodes, etc., rectifiers, amplifiers, oscillators, finishing with a chapter on the cathode ray tube.

Fitted into this pattern are four chapters of modern interest, semi-conductor devices, transistor amplifier and oscillators, wave shaping and control circuits, and fourthly, magnetic amplifiers. This latter chapter is written by a colleague and forms a good introduction to the subject.

The book is very descriptive and easy to follow, and appears to be exclusive of all mathematics. The odd equation appears here and there preceded by a reference number. It is of too elementary and shallow a nature to be of any serious value to electrical engineering or physics undergraduates in this country. It ought, however, to be available to those interested in electronics prior to university entrance. The book will also be appreciated by those scientists in other fields who want to understand the basis of electronic engineering.—J. C. WEST.

ALPINE PILOT. *Hermann Geiger. Cassell, London. Illustrated. 104 pp. 10s. 6d.*

At a Polish gliding school I attended in 1939, the standard method of landing was to fly toward the steep hillside and to land up the slope, irrespective of the wind direction. This procedure alarmed at first. What if we pulled the nose up too late or too soon? Later we learned that even on flat airfields pilots sometimes do this. One advantage of the uphill landing is the shortness of the landing run, even if the approach speed is high.

Hermann Geiger has adapted this technique for use in the high Alps with his Piper Super-Cub. His aeroplane has both wheels and skis and, with a stalling speed of only 30 m.p.h., can be landed comfortably in confined spaces. The upward snow slope should end in a level stretch, otherwise the aeroplane would tend to run backwards when the engine is stopped. Take-off is downhill—the rapid acceleration outweighs the possible lack of a headwind.

In case this sounds too easy, we should remind ourselves that these landings are often ten thousand feet up, the aeroplane often heavily loaded perhaps with a stretcher, and that the flying takes place close to the steep faces of the Alps. Apart from the effect on visibility of cloud and snow, the winds are unhelpful, especially those which blow vertically downwards.

It is not surprising to learn from Geiger's story that he first learned to fly a glider. Many glider pilots are used to rough, hilly fields and are familiar with the violent up and down currents found close to hills. Geiger learned to glide in 1928, at the age of 14, but soon managed to obtain power flying lessons. Twenty years of Alpine flying gave him the experience required for the high flying he now undertakes. At first sight, the helicopter seems to be the ideal aircraft, but Geiger has no criticism of his Piper.

His story is simply told and excellently illustrated. What is more photogenic than Alpine flying?—A. H. YATES.

MODERNER FLUGHAFENBAU. *Friedrich Kohl. Springer, Berlin, 1956. 129 pp. Illustrated. In German. DM 24.*

This is a comprehensive survey, in a fairly small volume, of the subject of airport design, layout and construction. It discusses the effect of turbo-jet air liners on airport design, the calculation of runway strength, and materials and methods of construction, including equipment used. The book ends with a chapter on the special needs of helicopters and heliport design and includes what appears to be a very useful Bibliography.

A TEXTBOOK OF SOUND. *A. B. Wood. Third Edition. Bell, London, 1955. 610 pp. Illustrated. 42s.*

This book has been thoroughly revised since the Second Edition was published in 1941, to include, and to present in text book form, the large amount of material, notably ultrasonics, hearing, noise, and technical applications, which has been published meanwhile. The book covers the requirements of students preparing for University degrees and is also well known and used as a reference book; the number of reprintings since the First Edition appeared in 1930 testifies to its worth.

NUMERICAL ANALYSIS. *Edited by John H. Curtiss. McGraw-Hill, New York, 1956. 303 pp. Diagrams. 73s.*

This volume contains nineteen—that is, all but two—of the papers presented at the Sixth Symposium in Applied Mathematics of the American Mathematical Society, held at Santa Monica City College, California, in August 1953. There is no need to emphasise the importance which is now given to computational work in the aeronautical field, and these papers are a valuable addition to the literature. Purely to give an idea of the type of paper presented, two of the titles are: "Numerical Results on the Shock Configuration in Mach Reflection" and "On the Solution of Linear Systems by Iteration."

RECORDS AND RESEARCH IN ENGINEERING AND INDUSTRIAL SCIENCE. *J. Edwin Holmstrom. Chapman and Hall, London, 1956. 491 pp. Illustrated. 60s.*

Dr. Holmstrom is a fine example of the adaptability of the trained scientific mind. Originally a Civil Engineer, he transferred his activities to information work and is now responsible for scientific documentation and terminology at UNESCO. The fact that a book on such an esoteric subject has reached a third edition is evidence of the esteem in which it is held. It deals with the basic principles of information tracing and retrieval and while any specialist librarian can, no doubt, criticise it from his own particular viewpoint, such criticism must, I think, be a matter of hair-splitting. As Holmstrom says in his Preface to the first Edition (and the sentence is fast becoming a classic) "The aim of this book is to teach the remarkable and stimulating facts that the whole of knowledge is available for everyone to use."

"Available" is a rather sweeping word in these days of security but that preface was written in 1940 or perhaps earlier.—F.H.S.

A.S.M.E. HANDBOOK. *Edited by Jesse Huckert. McGraw-Hill, New York, 1956. 687 pp. Diagrams. 99s.*

If all the mechanical engineering standards of the B.S.I. were put into one volume it would probably look like this and it would certainly be a boon to all mechanical engineers, workshops, factories and librarians. It is unfortunate, in many respects, that this is an American book but it does provide a first rate argument for international standardisation.

In his preface, the Editor says, "when the compilation of these tables was begun, I was unaware that so few of the data regularly used by designers could be condensed into a single volume." He has certainly done his best with such standards (chiefly American Standards Association) as gears, bar stock and shafting, bolts, screw threads, springs, aircraft and other tubing, electric motors and much else.

The book is divided into fifteen sections each of which is separately indexed and, certainly to any firm contemplating or indulging in American exports, it is an absolute "must."—F.H.S.

SYMPOSIUM ON MONTE CARLO METHODS. *Edited by H. A. Meyer. John Wiley, New York; Chapman and Hall, London, 1956. 382 pp. 60s.*

The Symposium of which this volume is the Proceedings was held in March 1954 at the University of Florida and was conducted by the Statistical Laboratory. The name "Monte Carlo Methods" is a new name for a comparatively old process, sometimes called "model sampling" and has been applied to any procedure which involves the use of sampling devices based on probabilities to approximate the solution of mathematical or physical problems. Twenty papers were presented at the Symposium and most have been rewritten since to include points raised during discussion. Photo-reproduction of an ordinary typed manuscript has been used and the publication is not a particularly attractive one; on the face of it, sixty shillings seems a lot of money.

MECHANICAL VIBRATIONS. *Fourth Edition. J. P. Den Hartog. McGraw-Hill, New York, 1956. 67s. 6d.*

This book grew originally from a course of lectures given to students in the Design School of the Westinghouse Company in Pittsburgh and was first published in 1934. Successive editions in 1940 and 1947, and now the Fourth Edition, testify to the worth of the book. In this Fourth Edition the number of problems has been substantially increased. New material has been added on Kármán vortices and on non-linear vibrations, with examples of cases which have appeared in practice since 1947 and changes have been made throughout to bring the subject up to date.

BIBLIOGRAPHIE DER VEROFFENTLICHUNGEN UBER DEN LEICHTBAU UND SEINE RANDGEBIETE IM DEUTSCHEN UND AUSLANDISCHEN SCHRIFTTUM. (*Bibliography of Publications on Light Weight Constructions and Related Fields in German and Foreign Literature.*) *H. Winter. Springer-Verlag, Berlin, 1955. 1003 pp. English and German. DM 80.*

German thoroughness is, of course, a byword and nowhere is this better exemplified than in matters connected with research of the printed word. I would venture to suggest that few finer samples of this thoroughness have been produced than this bibliography of 1,003 closely printed pages—a good £7-worth and absolutely invaluable to aeronautical stressmen.

The Preface and the Contents are both in English and German and from a casual glance at the body of the book it would appear that there are as many English references as there are German. Introductory and explanatory articles on the use of the Bibliography are also bilingual. It would be ungrateful to say that it is a pity the Subject Index is only in German.—F.H.S.

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# Reports

## AERODYNAMICS

### Boundary Layer—*see also* Thermo-Aerodynamics

*Flight experiments on the boundary layer characteristics of a sweptback wing. L. D. Allen and F. M. Burrows. CoA Report* 104. (*July* 1956).

The work considers the measurement in flight of the boundary layer characteristics of an untapered untwisted, 45° swept-back half wing of thin symmetrical section, mounted vertically on top of the fuselage of an Anson Mark I aircraft. The primary aim was to study the transition mechanism on swept-back wings, and an account is presented of the experiments so far performed with this object in view. Attention is also given to the design, development and construction of a suitable boundary layer traversing gear. For an incidence range of 0° to 10° and Reynolds numbers of 4, 4½, 5, 6, 7 and 8 million the static pressure distributions were determined and also the locations of transition for both surfaces using the creeping surface Pitot technique.—(1.1.2.1).

*Boundary layer separation in two-dimensional supersonic flow. G. E. Gadd and D. W. Holder. C.P.* 270. (1956).—(1.1.4.4).

*Exploratory investigation of the use of area suction to eliminate air-flow separation in diffusers having large expansion angles. C. A. Holzhauser and L. P. Hall. N.A.C.A. T.N.* 3793. (*October* 1956).

Tests were made at a mean inlet Mach number of 0·2 with area suction applied to conical diffusers with expansion angles of 30° and 50° and exit to inlet area ratios of 2.—(1.1.5.1).

*A factor affecting transonic leading-edge flow separation. G. P. Wood and P. B. Gooderum. N.A.C.A. T.N.* 3804. (*October* 1956).

The consequences of shock-wave boundary layer interaction are proposed as a factor that may be important in determining the conditions under which the change in flow pattern occurs. Some experimental evidence in support of the importance of this factor is presented.—(1.1.4.3).

*A low-speed experimental investigation of the effect of a sand-paper type of roughness on boundary-layer transition. A. E. von Doenhoff and E. A. Horton. N.A.C.A. T.N.* 3858. (*October* 1956).—(1.1.2.1).

### Compressible Flow

*Un metodo generale per lo studio del campo supersonico dietro onda d'urto aderente. L. Broglio. Monografie Sc. di Aero. N.*1. (1956).—(1.2.3.2).

*Conversion of inviscid normal-force coefficients in helium to equivalent coefficients in air for simple shapes at hypersonic speeds. J. N. Mueller. N.A.C.A. T.N.* 3807. (*October* 1956).

A correlation factor applicable for converting inviscid aerodynamic normal force coefficients of simple shapes in helium to equivalent coefficients in air is found by using calculations based on the shock-expansion method at Mach numbers of 12, 16, and 20.—(1.2.3).

*Tabulation of mass-flow parameters for use in design of turbo-machine blade rows for ratios of specific heats of* 1·3 *and* 1·4. *W. J. Whitney. N.A.C.A. T.N.* 3831. (*October* 1956).

Mass-flow tables are presented that enable a quick and accurate determination of the integrated average specific mass flow across a region where the endpoint velocities are known, commensurate with the assumptions that the total state is constant and the static pressure varies linearly between the two velocities. The tables include specific-mass-flow parameter and ratio of static to total pressure.—(1.2.1 × 1.5.3).

### Control Surfaces—*see* Loads

## Fluid Dynamics

*Report of the pressure panel on the definitions of quantities having the dimensions of pressure. C.P.* 281. (1956).—(1.4 × 30).

### Internal Flow—*see also* Compressible Flow

*Low-speed wake characteristics of two-dimensional cascade and isolated airfoil sections. S. Lieblein and W. H. Roudebush. N.A.C.A. T.N.* 3771. (*October* 1956).

Available low-speed wake data of two-dimensional cascade and isolated aerofoil sections are analysed to determine empirical and theoretical variations with downstream distance of such wake properties as minimum velocity, form factor, momentum thickness, full thickness, total-pressure loss, and ratio of mass-averaged to area-averaged loss.—(1.5.4.2 × 1.10.2.1).

*Investigation of a related series of turbine-blade profiles in cascade. J. C. Dunavant and J. R. Erwin. N.A.C.A. T.N.* 3802. (*October* 1956).

Series of directly related turbine blade shapes uniformly variable in camber are designed to satisfy the usual turbine-blade operating requirements of inlet air angle and turning angle. Low-speed cascade test results of five blade section and sample high-speed cascade tests for two blade sections of these series are presented. A method of properly cambering turbine blade shapes based on low-speed test results is given.—(1.5.4.3).

### Loads

*A simple method for calculating the span and chordwise loading on straight and swept wings of any given aspect ratio at subsonic speeds. D. Küchemann. R. and M.* 2935. (1956).

The methods of classical aerofoil theory are used to derive a general theory for wings of any given plan form. Accordingly, the general downwash equation is split into two parts: one the effective incidence, being due to the downwash induced by the vorticity component along the span; and the other, the induced incidence, which is due to the downwash induced by the streamwise vorticity component. The latter is related to the downwash in the Trefftz plane, and a downwash factor is introduced to include both the limiting cases of very small aspect ratio and of very large aspect ratio. With this method, the effects of wing thickness and of the boundary layer can easily be taken into account, as well as aero-elastic effects. Non-linearity of the lift due to tip vortices is also treated.—(1.6.1 × 1.10.1.2).

*Loading conditions of tailed aircraft in longitudinal manoeuvres. T. Czaykowski. R. and M.* 3001. (1956).

An analysis of aircraft response and loading conditions in symmetrical manoeuvres is presented with a particular recognition of the designer's needs. The analysis is based on the theory of aircraft response to elevator induced longitudinal manoeuvres. Basic response functions have been derived for the close, exponential type of elevator motion, and from these, general expressions have been obtained for various derived response quantities, such as tailplane loads, elevator hinge moments, normal accelerations at the tail, etc. A computational method which reduces the calculations to a routine is given.—(1.6.2).

*Low speed static and fluctuating pressure distributions on a cylindrical body with a square flat plate airbrake. T. B. Owen. C.P.* 288. (1956).—(1.6.3 × 1.3.4).

### Stability and Control—*see also* Aeroelasticity

*Multhopp's subsonic lifting-surface theory of wings in slow pitching oscillations. H. C. Garner. R. and M.* 2885. (1956).

This report is an extension of Multhopp's subsonic lifting-surface theory from steady flow to harmonic pitching oscillations of low frequency. The method is applicable to wings of arbitrary plan form. The theory is outlined and a description is given of calculations of pitching derivatives for circular, arrowhead and a family of delta wings; comparisons are obtained when the number of spanwise terms is varied. These results are compared with other theories; a development of vortex-lattice theory is shown to give satisfactory agreement, and the deficiencies of a purely steady theory are evaluated. The available wind tunnel data for oscillating wings of the selected plan forms is discussed.—(1.8.2.2).

*A simple method for calculating the characteristics of the Dutch roll motion of an airplane. B. B. Klawans. N.A.C.A. T.N.* 3754. (*October* 1956).

A simple method for calculating the characteristics of the Dutch roll motion of an aeroplane is obtained by arranging the lateral equations of motion in such form and order that an iterative process is quickly convergent.—(1.8.1.1).

*Flight investigation of the stability and control characteristics of a vertically rising airplane research model with swept or unswept wings and ×- or +- tails. R. H. Kirby. N.A.C.A. T.N.* 3812. (*October* 1956).

The take-off, landing, hovering, and transition flight characteristics of a propeller-driven, fighter-type, vertically rising aeroplane model were obtained from time histories of the flights and from the pilots' opinions of the flight characteristics.—(1.8).

*Experimental steady-state yawing derivatives of a 60° delta-wing model as affected by changes in vertical position of the wing and in ratio of fuselage diameter to wing span. B. M. Jaquet and H. S. Fletcher. N.A.C.A. T.N.* 3843. (*October* 1956).

Results are presented of an investigation conducted in the Langley stability tunnel to determine the effects of vertical position of the wing and the effects of the ratio of the fuselage diameter to wing span on the steady-state yawing derivatives of a 60° delta-wing model. The test Mach number was 0·13 and the test Reynolds number was $1{\cdot}65 \times 10^6$.—(1.8.1.2).

### Thermo-Aerodynamics

*A theoretical analysis of heat transfer in regions of separated flow. D. R. Chapman. N.A.C.A. T.N.* 3792. (*October* 1956).

An analysis is made of the rate of heat transfer to regions of separated flow in compressible streams. The physical mechanism postulated applies in principle to both laminar and turbulent flow, and to conditions where gas is injected into a separated region. Under the special conditions of zero boundary layer thickness at the separation point, the analysis yields relatively simple equations.—(1.9.1).

*Charts adapted from Van Driest's turbulent flat-plate theory for determining values of turbulent aerodynamic friction and heat-transfer coefficients. D. B. Lee and M. A. Faget. N.A.C.A. T.N.* 3811. (*October* 1956).

A modified method of Van Driest's flat-plate theory for turbulent boundary layer has been found to simplify the calculation of local skin-friction coefficients which, in turn, have made it possible to obtain through Reynolds analogy theoretical turbulent heat-transfer coefficients in the form of Stanton number. A general formula is given and charts are presented from which the modified method can be solved for Mach numbers 1·0 to 12·0, temperature ratios 0·2 to 6·0 and Reynolds numbers $0{\cdot}2 \times 10^6$ to $200 \times 10^6$.—(1.9.1 × 1.1.3.4).

### Wings and Aerofoils—*see also* Internal Flow and Loads

*The effect of transition wires on the pressure distribution over a N.A.C.A. 63A215 aerofoil section. K. D. Harris. CoA Note* 41. (*February* 1956).

Pressure distributions were measured over the surface of a N.A.C.A. 63A215 aerofoil section to determine the effect of transition wires on the lift and pitching moment characteristics. The tests were made at Reynolds numbers of $3 \times 10^5$ and $8 \times 10^5$.—(1.10.2.1).

*Measurement of lift, pitching moment and hinge moment on a two-dimensional cusped R.A.E.* 102 *aerofoil. A. S. Batson. C.P.* 272. (1956).—(1.10.2.2).

*On the measurement of supersonic aerofoil drag by pressure traverse. R. E. Meyer. A.R.L. Report A.* 97. (*May* 1956).

The drag in two-dimensional flow is expressed in terms of the distributions of static and stagnation pressures along a traverse line downstream of the aerofoil. Sources of error are discussed with regard to their effect on the accuracy of drag measurements in small tunnels at medium Mach numbers.—(1.10.2.1).

*Investigation of the aerodynamic characteristics of a model wing-propeller combination and of the wing and propeller separately at angles of attack up to* 90°. *R. E. Kuhn and J. W. Draper. N.A.C.A. Report* 1263. (1956).

Results are presented of a wind-tunnel investigation of the effects of slipstream for two large-diameter propellers on the aerodynamic characteristics of a wing model. The investigation covered angles of attack from −10° to 90° and thrust coefficients representing free-stream velocities from zero to the normal range of cruising flight.—(1.10.2.2 × 29.1).

### Helicopter Aerodynamics

*Charts for estimating the hovering endurance of a helicopter. R. A. Makofski. N.A.C.A. T.N.* 3810. (*October* 1956).

As a means of comparing the performance capabilities of various helicopter propulsion systems, charts are presented for estimating the hovering endurance of a helicopter in the form of a hovering-endurance parameter as a function of the ratio of total fuel load to helicopter initial weight for a range of initial thrust coefficients from 0·002 to 0·012 and for values of rotor mean lift coefficient from 0·24 to 0·72. The charts are presented for a helicopter having rotor blades with ideal twist.—(1.11).

### Testing and Instruments

*Characteristics of the flow field over the mid-upper fuselage of Lancaster P.A.* 474. *F. M. Burrows. CoA Note* 36. (*January* 1956).

The series of tests described were conducted to determine the characteristics of the flow field over the mid-upper fuselage of Lancaster P.A. 474. The range of the tests was to include a determination of the distributions of total head, static pressure and velocity together with the flow directional characteristics in the pitching plane for a number of aircraft flight configurations. Curves are presented showing the flow directional characteristics and the distributions of static pressure and velocity in the region of investigation.—(1.12.2).

*A note on derivative apparatus for the N.P.L.* 9½ *inch high speed tunnel. J. B. Bratt. C.P.* 269. (1956).

New equipment is described briefly for measuring derivatives on finite aspect ratio models with trailing edge flaps in the N.P.L. 9½ inch high speed tunnel. Some account is also given of considerations leading to the choice of method.—(1.12.4).

*Automatic indicating and recording data systems for wind tunnels. J. B. D'Andrea. AGARD Report* 16. (*February* 1956).

The more simple and relatively less expensive systems for the rapid and accurate recording of raw data in tabulated, punched card and/or tape, and plotted form are described. A particular system described is that used in the 10 ft. Transonic Wind Tunnel at the Wright Air Development Center, and a review is included of other types of instrumentation and recording equipment that could be similarly used.—(1.12.1).

*An air-flow-direction pickup suitable for telemetering use on pilotless aircraft. W. L. Ikard. N.A.C.A. T.N.* 3799. (*October* 1956).

A vane-type air flow direction pick-up is described which is suitable for telemetering angle-of-attack and angle-of-sideslip data from rocket-propelled pilotless aircraft models. Test results which are presented show that the device performs well under high accelerations and is stable throughout a Mach number range from subsonic to above a Mach number of 2·5.—(1.12.2).

## AEROELASTICITY

*The oscillating aerofoil in subsonic flow. W. P. Jones. R. and M.* 2921. (1956).

A relatively simple method for calculating the aerodynamic forces on an oscillating aerofoil is developed and used to derive the aerodynamic coefficients for $M=0{\cdot}7$, 0·8 and 0·9 for a range of frequency parameter values.—(2 × 1·8).

*Flutter calculations on a rudder with trailing-edge spoiler. Ll. T. Niblett. C.P.* 277. (1956).—(2).

## AIRCRAFT OPERATION

*See also* STRUCTURES—LOADS

*Assessment of the aircraft for its part in a defence system. R. P. Dickinson. AGARD Report* 32. (*February* 1956).

This report discusses the relative importance of the various aspects of behaviour of the interceptor fighter aircraft in relation to its part in the overall defence system. Features governing the success of the aircraft in using its weapons effectively are discussed.—(5).

## MATERIALS

*See also* STRUCTURES—THEORY AND ANALYSIS

*The source of the nitrogen impurity in electrodeposited chromium. N. Ryan. A.R.L. Note Met.* 4. (*August* 1956).

The nitrogen content of chromium deposited from an electrolyte of chromic acid and sulphate was not influenced appreciably by the presence of dissolved nitrogen in the bath. However, additions of nitrate impurity to the electrolyte resulted in a marked increase in the nitrogen content of the chromium, and this factor is considered to be responsible for the minor nitrogen impurity normally found in electrolytic metal.—(21.1).

*The effect of grain size on the flexural fatigue strength of L40 aluminium alloy. J. M. Finney and W. W. Johnstone. A.R.L. Note S.M.* 231 (*July* 1956).

Flexural fatigue tests were made on specimens, both unnotched and notched with a drilled hole, cut from L40 aluminium alloy bulb angle extrusions containing fine, intermediate, and coarse grains. The tests indicated that the fatigue strength at $10^6$ cycles of the coarse grained specimens was lower than the specimens containing both fine and intermediate sized grains.—(21.2.2 × 31.2.2.3.1.2).

*Effects of intermittent versus continuous heating upon the tensile properties of* 2024-*T4*, 6061-*T6 and* 7075-*T6 alloys. G. W. Stickley and H. L. Anderson. N.A.C.A. T.M.* 1419. (*August* 1956).

The object of these tests was to determine the effects of intermittent and continuous heating at 300° and 400°F., for total periods of 100 and 200 hours, upon the tensile properties of 2024-T4 and 6061-T6 alloy rolled-and-drawn rod and 7075-T6 alloy extrusions, at room temperature and at the temperature of heating. The effects of intermittent heating were found to be cumulative and the same as for continuous heating.—(21.2.2).

*Heat-capacity measurements of titanium and of a hydride of titanium for temperatures from* 4° *to* 15° *K. including a detailed description of a special adiabatic specific-heat calorimeter. M. H. Aven et al. N.A.C.A. T.N.* 3787. (*October* 1956).

Results of heat-capacity measurements on samples of pure titanium and of a hydride of titanium are presented and compared with calculated results. The measurements were made using a special adiabatic specific-heat calorimeter which is described in detail.—(21.2.2 × 21.6.2).

*Static strength of aluminum-alloy specimens containing fatigue cracks. A. J. McEvily et al. N.A.C.A. T.N.* 3816. (*October* 1956).

Seven configurations of specimens made of 2024 and 7075 aluminium-alloys in both rolled and extruded form were subjected to repeated axial loads until fatigue cracks of various lengths were formed. The specimens were then subjected to static tests to determine the residual static strength. Small cracks resulted in disproportionately large reductions of static strength. A simple method of analysis which predicts the observed results was developed and described.—(21.2.2 × 33.2.4.13.1).

## MATHEMATICS

*A short note on the checking of contractants. J. Guest. A.R.L. Note S.M.* 235. (*September* 1956).

A simple means of checking contractants has been devised which is considered essential to a computer.—(22).

## PROPELLERS

*See* AERODYNAMICS—WINGS AND AEROFOILS

## REFERENCE LITERATURE

*See* AERODYNAMICS—FLUID DYNAMICS

## FATIGUE

*See also* MATERIALS AND STRUCTURES—THEORY AND ANALYSIS

*Fatigue loadings in flight: loads in the wing of a Varsity. A. Burns. C.P.* 285. (1956).

Data are presented on the number of load cycles of various magnitudes occurring in the wing of a Varsity in normal ground and flight conditions. The conditions include taxying, take-off, landing, and flight in turbulence. The relative importance of the loads in the different conditions is illustrated by reference to the loads in a typical flight. A relationship is determined between wing loads and accelerations in turbulence so that the test results can, if required, be related to gust data obtained operationally by means of the counting accelerometer.—(31.1.1).

## STRUCTURES

LOADS

*Fatigue loadings in flight: loads in the fuselage and nose undercarriage of a Varsity. E. W. Wells. C.P.* 287. (1956).

Flight tests have been made on a Varsity to obtain data on the fatigue loads in the fuselage and the nose undercarriage. The data is tabulated in terms of the number of load ranges of a given magnitude occurring during various ground and flight conditions. An estimate is made of the loads in a typical operational training flight to show the relative importance of the various conditions. A relationship is established between the fuselage loads and the accelerations at the aircraft c.g. when flying in turbulence; this enables the results from the flight tests to be linked to operational data obtained on gusts.—(33.1.1).

*Seat design for crash worthiness. I. I. Pinkel and E. G. Rosenberg. N.A.C.A. T.N.* 3777. (*October* 1956).

On the basis of deceleration data obtained in full-scale crashes, a description of crash deceleration pulses is presented which is suitable for seat design. Charts are presented for obtaining the maximum deceleration loads experienced by the seat and passenger in response to their crash deceleration pulses. A method is presented for determining the seat strength, spring stiffness, and deformation beyond the elastic limit required to serve in a given crash deceleration pulse. Measurements of passenger decelerations in full-scale laboratory and crash studies are given.—(33.1.2 × 5.3).

THEORY AND ANALYSIS—*see also* MATERIALS

*Determination of influence coefficients. S. Levy. AGARD Report* 41. (*February* 1956).

The method of consistent deformations for determining influence coefficients of delta wings is reviewed. Computational difficulties which may arise in applying this method are discussed. A review is given of strain energy and differential equation methods for computing influence coefficients.—(33.2.3.2).

*Tensile strength and time to fracture tests on Redux bonded 75 S-T clad single lap joints at temperatures varying from room temperature to* 80°*C. A. Hartman. N.L.L. Report M.* 2009.

Tensile and time to fracture tests were carried out on Redux bonded 75 S-T clad single lap joints at temperatures from room temperature to 80°C. The curing used was half an hour at 145, 160 and 175°C. The results suggest that a determination of the tensile or the long-term strength at a sufficiently high temperature, *e.g.* 80°C, will be a good check on the curing of the adhesive. Use of Redux film instead of Redux liquid and powder required a 10° to 15°C higher curing temperature to reach the same strength at elevated temperature.—(33.2.4.13.9 × 21.3.3).